CHARACTERIZATION AND DEVELOPMENT OF EMISSION QUALITY INDEX FOR PASSENGER CARS

A thesis ***Submitted***

in partial fulfilment of the requirements for the award of the degree of

DOCTOR OF PHILOSOPHY

In

ENVIRONMENTAL ENGINEERING

By

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(En. No. - 2K14/PhD/EN/04)

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DECLARATION

I hereby declare, that the research work presented in this thesis entitled "Characterization and development of emission quality index for passenger cars" is original and carried out by me under the supervision of Dr. Rajeev Kumar Mishra, Assistant Professor, Department of Environmental Engineering, Delhi Technological University, Delhi, and Dr. Govind Pandey, Professor, Civil Engineering Department, Madan Mohan Malaviya University of Technology, Gorakhpur, and being submitted for the award of Ph.D. degree to Delhi Technological University, Delhi, India. The content of this thesis has not been submitted either in part or whole to any other university or institute for the award of any degree or diploma.

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CERTIFICATE

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ABSTRACT

Most of the developing countries still have various makes of petrol-driven cars dominating the overall passenger vehicle fleet. In such countries, the emission certification policy for in-use vehicles remains an area of concern, making the I/M (Inspection and Maintenance) program less effective. Thorough investigation of the exhaust emission from such cars is required to explore and address this concern. In this connection, the present thesis provides an insight into the effect of vehicle variables on tailpipe emission parameters from an exclusively larger and heterogeneous dataset of in-use cars (n = 1580). reiterated that not only the vehicle variables such as age, mileage, emission norm and maintenance category, but also two engine variables, i.e., aspiration type and fuel mixing conditions had a more significant and direct influence on tailpipe parameters, namely, CO, HC, CO_2, O_2, λ and AFR (Carbon Monoxide, Hydrocarbon, Carbon Dioxide, Oxygen, Lambda and Air-Fuel Ratio respectively). Stronger correlations were found with the relatively larger (considering age, R^2 for $CO_{idle} = 0.88$, $HC_{idle} = 0.73$, $\lambda_{f.idle} = 0.74$, $AFR_{f.idle} = 0.73$ and considering mileage, R^2 for $CO_{idle} = 0.75$, $HC_{idle} = 0.67$, $\lambda_{f.idle} = 0.62$, $AFR_{f.idle} = 0.61$ for whole dataset) and diverse make-wise (R^2 values fared even better, 0.87 – 0.93 for CO and 0.69 – 0.77 for HC) data collected during the study. The present research provides a first-hand comprehensive analysis of the effect of stringency of the emission norms and maintenance category on the exhaust emission from in-use cars. The polynomial emission equations generated by the study can reliably predict the emission levels for CO and HC basis the age and / or mileage of the cars. Further, the results recommend the policy measures to be taken up, to upgrade the existing emission certification infrastructure and phasing-out policy of cars.

Keeping in view the significant number of diesel-driven passenger cars in the existing light motor vehicle fleet in Delhi, India, a case study on smoke emission measurement from 460 number of such cars was conducted. Smoke exhaust data was collected from the diesel cars while the vehicles presented themselves for periodic renewal of pollution under control (PUC) certification at authorized emission testing centres across Delhi, India. Along with the smoke emission, various vehicle and engine-related aspects, supposed to affect tailpipe smoke emission, were also recorded aiming at data analysis for two datasets, namely whole and top 5 makes. The smoke density under no-loading condition in the free acceleration test

mode was measured. The research study reported a strong correlation between vehicle parameters, such as, age, mileage, maintenance category, emission norm and engine aspiration; and the smoke emission (R^2 values for vehicle age and mileage vs. smoke emission for whole dataset = 0.872 and 0.873, respectively). Top 5 make-wise correlations fared even better (R^2 for age and mileage vs. emission in the range of 0.85 – 0.92 and 0.86 – 0.93, respectively). Further, the predictive emission equations using best-fit trendlines were also developed for both datasets. Such equations may be used by the car manufacturers to adopt a suitable strategy for tuning of engine or vehicle as such, to retain their cars in the longer state of compliance to the extant emission norms, Further, the research recommends including vehicle mileage as an important factor in upgrading the existing inspection and maintenance programs, especially in the developing countries.

The I/M (Inspection/Maintenance) programs exist in most countries, aiming at vehicular emission reduction through exhaust emission monitoring and compliance policy to the extant norms. However, considering the absence of an intra-vehicle approach, the higher success rate of vehicles towards compliance policy, remains a grey area. The present research work attempts to examine this issue through the application of an Exhaust Emission Index (EEI) for petrol-driven cars. The study observed two different scales finding that the BS (Bharat Stage) emission norm scale method reports lower ranges of EEI compared to LS (Linear Scale) method ($EEI_{min-BSNS}$ = 1.12 and EEI_{min-LS} = 1.25; $EEI_{max-BSNS}$ = 20.70 and EEI_{max-LS} = 29.54). The LS method and the maximum operator form (MOF) of aggregation are recommended as these can find the highest number of non-compliant cars (21.81 % and 12.03 % of the ‘poor’ class respectively) in the whole fleet tested. The EEI gives more scientific approach to the vehicular emission evaluation like what AQI (Air Quality Index) does in case of the ambient air quality. It helps the vehicle owners know their car’s emission status as a quick reference index (EEI). The accurate status of such emission further helps the policymakers affect the better phasing-out norms.

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LIST OF ABBREVIATIONS

AFR – Air Fuel Ratio
ANOVA – Analysis of Variance
API – Air Pollution Index
AQI – Air Quality Index
ARAI – Automotive Research Association of India
ARI – Aggregate Risk Index
ASC – Ammonia Slip Catalyst
AWD – All Wheel Drive
BHP – Brake Horse Power
BP – Brake Point
BS – Bharat Stage
BSNSM – Bharat Stage Norm Scale Method
BTEX – Benzene, Toluene, Ethyl benzene and Xylene
CC – Cubic Capacity
CI – Compression Ignition
CO – Carbon Monoxide
CO_2 – Carbon Dioxide
CPCB – Central Pollution Control Board
CRDI – Common Rail Direct Injection
CVMR – Central Motor Vehicle Rules
DCS – Direct Combustion System
DDPCs – Diesel-Driven Passenger Cars
DI – Direct Injection
DOC – Diesel Oxidation Catalyst
DOHC – Double Overhead Cam
DPF – Diesel Particulate Filter
ECS – Electro-Chemical Sensor
EEI – Exhaust Emission Index
EGR – Exhaust Gas Recirculation
EU – European Union

FAIPL – Fiat Auto India Private Limited
FAQHI – Fuzzy Air Quality Health Index
FAQI – Fuzzy Air Quality Index
FAST – Free Acceleration Smoke Test
FI – Fast Idle
FIPL – Ford India Private Limited
FWD – Front Wheel Drive
GMIPL – General Motors India Private Limited
HC – Hydrocarbons
HCIL – Honda Cars India Limited
HKAQI – Hong Kong Air Quality Index
HMIL – Hyundai Motors India Limited
HML – Hindustan Motors Limited
HSU – Hartridge Smoke Unit
I/M – Inspection & Maintenance
IBM – International Business Machines
ICCT – International Council on Clean Transportation
ICS – Indirect Combustion System
IR – Infrared
IUCP – In-Use Confirmatory Program
IUVP – In-Use Verification Program
JDL – Jato Dynamics Limited
LDVs – Light-Duty Vehicles
LMVs – Light Motor Vehicles
LOA – Limits of Agreement
LSAF – Linear Sum Aggregation Form
LSM – Linear Scale Method
MBIPL – Mercedes Benz India Private Limited
MM – Milli Meter
MML – Mahindra Motors Limited
MOF – Maximum Operator Form

MoRTH	–	Ministry of Road Transport and Highways
MPFI	–	Multi-Point Fuel Injection
MS	–	Microsoft
MSIL	–	Maruti Suzuki India Limited
NAAQS	–	National Ambient Air Quality Index
NCT	–	National Capital Territory
NDIR	–	Non-Dispersive InfraRed
NM	–	Newton Meter
NMIPL	–	Nissan Motors India Private Limited
NOx	–	Oxides of Nitrogen
NSC	–	NOx Storage Catalyst
OICA	–	Organisation Internationale des Constructeurs d'Automobiles
PCVE	–	Programs to Control Vehicle Emissions
PDPCs	–	Petrol-Driven Passenger Cars
PEMS	–	Portable Emission Monitoring System
PGM-FI	–	Programmed Fuel Injection
PM	–	Particulate Matter
PNC	–	Particle Number Count
PPM	–	Parts Per Million
PUC	–	Pollution Under Control
RAPI	–	Revised Air Pollution Index
RDE	–	Real-Driving Emission
RIPL	–	Renault India Private Limited
RMSF	–	Root Mean Square Form
RPM	–	Revolutions Per Minute
RR	–	Relative Risk
RSPF	–	Root Sum Power Form
RTO	–	Regional Transport Office
RWD	–	Rear Wheel Drive
SAIPL	–	Skoda Auto India Private Limited
SCR	–	Selective Catalytic Reduction
SE	–	Smoke Emission
SI	–	Spark Ignition
SOHC	–	Single Overhead Cam

SOx	–	Oxides of Sulphur
SPM	–	Suspended Particulate Matter
SPSS	–	Statistical Package for Social Sciences
SUV	–	Sport Utility Vehicle
TKMPL	–	Toyota Kirloskar Motors Private Limited
TML	–	Tata Motors Limited
USA	–	United States of America
USEPA	–	United States Environmental Protection Agency
UV	–	Ultraviolet
VE	–	Vehicular Emission
VWIPL	–	Volkswagen India Private Limited
WAF	–	Weighed Additive Form
WHO	–	World Health Organization

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Environmental pollution is an alarming concern not only to humanity but to every life form and holistically speaking, to the whole planet. Various anthropogenic activities have further been worsening the ‘never-before’ deterioration in the environmental quality in multiple ways and through different means. Of all other types, air pollution remains one of the most challenging problems of the present times. Broadly speaking, human activities generate three main sources of air pollution: stationary or point, mobile, and indoor. In developing countries, especially in rural areas, indoor air pollution from using open fires for cooking and heating may be a serious problem. Industries, power plants, process and production houses located in different parts of the country pollute the air as stationary sources. But in urban areas of developing and developed countries, the predominance of mobile sources of pollution like vehicular pollution is conspicuous with reference to the overall air quality problem.

Increasing urbanization, industrialization and motorization have led to the highest ever emission of air pollutants worldwide. The motor (vehicle) density per capita is a significant indicator of motorization trends globally. The United States of America (U.S.A.) had roughly 650 vehicles per 1000 of its population in 1990, which rose to 855 in the year 2021 (growing at about 7.99 % per decade on average). Germany and Japan had vehicle density figures of 435 and 450 in 1990, which increased to 628 and 624 respectively in 2020, thereby registering an average decennial growth of over 10 %. On the other hand, India, which had a vehicle density of nearly ‘10’ in 1990, has shot to the figure of 61 in the year 2020, registering an average decadal growth of approximately 28 %.

Similar is the case of the total number of registered vehicles. India had about 172 million vehicles till March 2014 compared to just 80 million registered vehicles till same period of 2007. However, the number has increased to 313 million by March 2020. Similarly, the number of registered vehicles in the national capital city (Delhi) was 5.19, 8.29 and 11.91 million in March 2007, 2014 and 2020 respectively. The numbers have been on the sharp rise, particularly after the major economic reforms brought about by the then Government of India in 1991 paving the way for liberalization and globalization.

Vehicular emission contributes to about 65-70% of air pollution load in urban India, of which 60% comes from tailpipe exhaust and the remainder from the crank-case blow-by and evaporative emission. Both petrol and diesel-driven vehicles tend to emit some harmful exhaust emissions, such as CO (Carbon Monoxide), unburned HCs (Hydrocarbons), NO_X (Oxides of Nitrogen), SO_X (Oxides of Sulphur) and smoke or PM (Particulate Matter). Usually, the NO_X and SE (smoke) are relatively higher in diesel engines compared to petrol engines.

Both the indigenous and overseas petrol and diesel cars in India are equipped with internal combustion (IC) engines differentiated by their fuel ignition method. The petrol engines working on the Ott cycle have a spark ignition (SI) system, whereas the diesel engines following the principle of the diesel cycle use a compression ignition (CI) system. The petrol-driven vehicles are still a popular choice in the country occupying the largest chuck of privately-owned light-duty passenger cars. Diesel-driven cars follow closely when commercial passenger cars are accounted for (such as taxis and cabs other than private cars).

It is well established that the effect of air pollution is seen in view of the scale it can reach and the type of receivers it can adversely affect for e.g., local, regional and global scales of reach and human, plants, natural environment, and material respectively. The effects have been demonstrated to range from respiratory and heart problems, increase in green-house gases and global warming, acid rain, depletion of ozone layer, eutrophication, effects on wildlife, smog and soot, pollen and mold, etc., some of these being visible and some not.

The major pollutants emitted by motor vehicles, including CO, NO_X, SO_X, HC, SPM etc., have damaging effects on both human health and ecology. The human health effects of air pollution vary in the degree of their severity, covering a range of minor impacts to serious illness, as well as premature death in certain cases. Most of the legacy air pollutants are believed to directly affect the respiratory and cardiovascular systems. In particular, high levels of SO_2 and SPM are associated with increased mortality, morbidity and impaired pulmonary function. Lead prevents hemoglobin synthesis in red blood cells in bone marrow, impairs liver and kidney function and causes neurological damage. Outdoor air pollution is the fifth largest killer in India, with about 620,000 premature deaths from air pollution-related diseases every year.

Comparing the scenarios of emission certification policy in India versus the U.S.A., the PCVE (Programs to Control Vehicle Emissions) appears to be more effective because of the technical and legal framework put in place by the Environmental Protection Agency (U.S.E.P.A.), which is successful in implementation and compliance of the pertinent policies. Except for the U.S.A., E.U. (European Union) and other developed countries, plus China and Brazil, the emission certification policies for in-use passenger cars in most developing countries are struggling to meet the overall vehicular emission reduction goals. Hence, a comprehensive exploratory analysis of exhaust emission compliance of the petrol and diesel-driven light-duty passenger cars to the in-use emission norms is required covering a large and heterogeneous make-wise dataset.

Another problem is intra-vehicle assessment of tailpipe emission, for example, the CO value in tailpipe emission may be lower than the prescribed norm, but that of HC may be higher and vice-versa. In such a case, a vehicle may be compliant for CO, but non-compliant for HC and vice-versa too. It is, therefore, difficult to rationally declare the compliance or non-compliance of a vehicle in view of the prescribed in-use emission norm.

In other words, the vehicle’s ‘pass’ performance ascertained in the I/M (Inspection and Maintenance) testing will be questionably supported by the fact that over 80% of the vehicles come clear in such testing. Such emission compliance testing for in-use vehicles critically needs a tool that could indicate their emission performance in an easy-to-interpret statistical form (index) and suggest further course of action in what could render or keep them in a state of compliance to the relevant norms. This very lack of a quick tool to indicate towards intra-vehicle assessment of compliance to ‘in-use’ emission norm is one of the key objectives of the present research work.

1.2 Need for and importance of the work

As the number of vehicles is exponentially rising in the country and there is a cut-throat rivalry among the manufacturers of passenger cars, it is essential to look into the effect of vehicle and engine-related independent variables on tailpipe emission. This is required in particular reference to light-duty passenger cars, which occupy a significant proportion of the overall urban fleet of petrol and diesel-driven cars. As such, it is necessary to quantify the emission levels of CO, HC, CO_2, O_2, SE (smoke emission) and other parameters, such as λ and AFR (Air-fuel ratio), from different makes and models of such cars plying on the roads of Delhi, India.

With a greater emphasis on controlling the emissions from vehicles, BHARAT Stage norms have been adopted in India *at par* with Euro standards and now it is mandatory for the manufacturers of the vehicles to equip all the vehicles with appropriate pollution control systems. Even though the vehicle coming out of the factory is supposed to have pollution under control yet the compliance status of the in-use vehicles with respect to vehicle-related factors is generally not known and the literature covering this aspect is scantily available. Evidently, if the behaviour of the vehicle in terms of the emission levels with respect to some important vehicle-related factors like vehicle age, vehicle mileage and maintenance aspects is properly understood, suitable steps can be taken accordingly to keep the emissions from the vehicle under control overcoming the effect of such factors.

At the same time, the effect of other vehicular parameters, including the engine (e. g., Make, Model, Body type, Kerb weight, Status of registration life, Emission norm at manufacturing, Transmission type, Drivetrain type, Fuel, Engine Capacity, Stroke, Maximum power, Maximum torque, Compression ratio (:1), Cylinder bore, Piston stroke, Aspiration type, No. of cylinders, No. of valves per cylinder, Valve configuration, Fuel distribution system etc.) which relate to the design and production of vehicles should also be known to suggest certain guiding factors to the automobile industry from the point of view of ensuring the emissions are under control.

In the present work, the petrol and diesel-driven passenger cars appearing for the periodic emission compliance certification (i.e., PUC – pollution under control) at various testing centres located across Delhi, were investigated for their tailpipe (emission) parameters over a period of time and the data pertaining to the vehicle and engine-related aspects were collected. The data were analyzed to ascertain the effect of various vehicle and engine-related parameters on the emission level of top make and models of petrol and diesel-driven passenger cars. Based on the study, suitable recommendations have been made.

1.3 Objectives of the study

Considering the significance of the impact of vehicular emissions and its important contribution to the problem of air pollution, the work has been undertaken with the following objectives:

1) Review of literature to ascertain the recent findings in the area of tailpipe emission, important vehicle-related parameters and methodologies of measuring the emissions from both petrol and diesel-driven passenger cars, including research gaps.
2) To quantify / characterize and investigate the effect of vehicle-related parameters, such as age, mileage, stringency (or progression) of the emission norms, maintenance records (i.e., I/M – Inspection and Maintenance), vehicle weight, transmission type, drivetrain type etc. on tailpipe emission parameters, such as CO, HC, CO_2, O_2, λ (Lambda) and AFR (Air Fuel Ratio) as well as the smoke emission (SE).
3) To quantify / characterize and investigate the effect of various engine-related variables, namely, power, torque, cubic capacity, compression ratio, cylinder bore, piston stroke, aspiration type, number of cylinders, number of valves per cylinder, valve configuration and fuel mixing conditions etc. on CO, HC, CO_2, O_2, λ (Lambda) and AFR (Air Fuel Ratio) as well as the smoke emission (SE).
4) Comprehensive assessment of the compliance of petrol and diesel-driven cars towards the in-use emission norms.
5) Development of Exhaust Emission Index (EEI) for petrol-driven passenger cars using the emission data collected (CO and HC).
6) To suggest changes in the extant emission regulation policy and I/M programs to improve efficiency.
7) Suggestions relating to the control of tailpipe emission with reference to the in-use vehicle emission norms and classification criteria of vehicles on the basis of EEI.

With these objectives in view, the literature review, materials and methods, data analysis, results and discussion followed by recommendations and conclusion have been presented.

1.4 Organization of the thesis

The thesis has been organized into 5 chapters. A brief outline of the chapters is presented hereafter:

Chapter 1 presents the introductory part of the thesis, which has been sub-divided into introduction, need for and importance of the work, objectives of the study and the organization of the work. Chapter 2 deals with the review of literature, in which pertinent literature from various sources has been reviewed to enable the study to be taken up in right perspective and planned manner. The research design and methodology have been described in chapter 3, which incorporates the actual methodology of the fieldwork, data collection and analysis tools. Next to this chapter is chapter 4, which covers the analysis of data, results and discussion part of the thesis. In this chapter, the analysis of the field data has been carried out and the results have been discussed critically. The conclusions based on the study's outcome have been incorporated in chapter 5, along with future prospects or scope of further research.

CHAPTER 2

LITERATURE REVIEW

Keeping in view the wide objectives of the research, the literature review chapter is divided into four parts to have specific coverage of different research aspects, namely, petrol-driven passenger cars; diesel-riven passenger cars; emission compliance, and exhaust emission index; followed by the concluding remarks.

2.1 Petrol-driven passenger cars

As most city areas are transforming into urban conglomerations, the rise in motor vehicle density is following closely with global expansion. This scenario (particularly in developing countries) is giving rise to the aggregation of a larger number of motor vehicles and their lifetime spent in the same urban boundary limits, thereby causing tremendous pressure on the well-being of the urban environment. These urban areas emit a significant proportion of air pollutants globally and can often be associated with poor air quality. (Lawrence et al. 2007; Butler 2013).

In the latest period of 10–15 years, worldwide passenger car sales have embraced a very high growth of 17.97 % to 21.16 % (comparing the sales data of 2019 with 2010 and 2005 respectively). The number of 45.25 million passenger cars sold globally in 2005 has almost doubled to 90.42 million only in 14 years span (OICA 2019). The vehicular growth rate has surpassed the urbanization rate; with more than 90 % of the daily vehicular sales linked to private ownership (Perappadan 2012; Government of Delhi 2020).

In such countries, increasing ambient air pollution has caused over 4.2 million deaths annually, along with many cases of respiratory illnesses (WHO 2019). Furthermore, exposures to vehicular emissions (VE) have also been reported to prompt various human health consequences including, but not limited to, cardiovascular disease, pulmonary function decline, cancer and mortality (Ogunseye et al. 2018; Rice et al. 2015: Wong et al. 2019).

Megacities, particularly in developing nations, have reported over 70–80% of air pollution, which is attributed to vehicular emissions caused by a large chunk of older vehicles exhibiting poor vehicle maintenance, inadequate road infrastructure and low fuel quality (Badami 2005; Singh et al. 2007; Wang et al. 2010; Pandey et al. 2016). Among the criteria pollutants, CO (Carbon Monoxide) is one of the most significant pollutants emitted by the transport segment, contributing to about 90% of total emissions with Hydrocarbons (HCs) following closely.

This heterogeneous fleet of cars in Delhi is subject to periodic emission compliance testing in most of the developing countries, which allows them to remain in operation only upon passing the test. This testing is an integral part of the existing I/M program, which consists only of non-loaded idle or fast idle measurement of CO and HC from the vehicle's tailpipe while stationary. Earlier researches have expressed the need to understand the emission characteristics of vehicles with a larger, heterogeneous dataset (Kazopoulo et al. 2005) with more model years (Beydoun et al. 2006) and in the context of more parameters concerning vehicles, age, mileage, maintenance, applicable emission norms and various engine-related features as the key ones (Pandey et al. 2016).

Analysis of test failure and detailed regression analyses of I/M data for CO and HC from various states in the United States concerning vehicle features and emissions revealed that the likely failure rate of older and poorly maintained vehicles for the overall emission was significantly higher (Beydoun et al. 2006). A study on the Japanese scrappage scheme found that CO_2 (Carbon Dioxide) emissions would only decrease if users retained their new gasoline passenger vehicles for at least 4.7 years. This decrease was predominantly attributable to the better combustion efficiency of the newer vehicles (Kagawa et al. 2013).

In the case of the Italian fleet of passenger cars, annual mileage was found to drop significantly with age. Both diesel and gasoline cars drove half the annual distance when they reached an average age of approximately 8 years; hence, mileage must be considered along with the vehicle age while estimating emissions from the transportation sector (Caserini et al. 2013). An investigation of 100 gasoline cars for their exhaust emission (CO and HC) under a basic I/M program in Lebanon was conducted. The vehicles reported higher failure rates indicating the need to develop country-specific emission standards. Proposed Lebanese standards had CO and HC ranges of 1.5±0.5 (%) and 250±36 (ppm) respectively. The smaller sample size was a major limitation of the study, implying the need for representative sampling to refine the outcomes (Kazopoulo et al. 2005).

During idle operation of the vehicles, the engine does not operate at peak temperatures resulting in high brake-specific fuel consumption and incomplete fuel combustion that leads to high emission formation (both CO and HC) as well as fuel residue in the exhaust (Sanchita et al. 2014). An investigation of tailpipe CO and HC from 300 petrol-driven passenger cars of Maruti make in India found both CO and HC to be higher in case of fast idling conditions. In both the test scenarios, the tailpipe emission of CO and HC was positively correlated with vehicle age and mileage. Although, the need to refine this correlation was felt with a more intensive and make-wise dataset (Pandey et al. 2016).

A direct relationship between AFR and λ in the form of polynomial equations with high accuracy was determined based on field data and measurements. It can help in understanding the relation between AFR and λ and determine the value of any one of them if the other value is known using the estimation equations developed through the data analysis (Al-Arkawazi 2019). Using the significant model coefficients and corresponding log odds values, a probability model was constructed to show the probability of compliance to the emission norms. For instance, a 15 years old and private car used in Ogun State, Nigeria, had 79% probability of complying with the Euro II (2.5%) standard. The probability can therefore be extrapolated for any aged vehicle in-use (Moonsammy et al. 2021).

The extent of the reduction in NO (Nitrogen Oxide) emissions by each successive Euro standard was demonstrated clearly. The benefit of moving from earlier to later emissions standards to reduce overall NO emissions from petrol cars was found to be clear, when the proportion of each category in the overall observed fleet was taken into account (Rhys-Tyler et al. 2011). A comprehensive inspection and remedial maintenance program are extremely important to curb and control vehicular emissions levels. Accordingly, like many other countries, most Asian countries have taken various initiatives to implement an effective inspection and maintenance program (Dandapat et al. 2020).

I/M programmes, mostly, have two types of emission testing, e.g., basic and advanced. The most common is the measurement of CO and HC values in the exhaust while the vehicle is idling. The idle test was originally developed with a view to detect a large proportion of malfunctioning or maladjusted engine. To help reduce the false failures with this test, some I/M programs require pre-conditioning at 2500 revolutions per minute (rpm) with no load, referred to as fast idle testing (Pandey et al 2016). In spite of its introduction many years ago, the idle testing has some advantages, such as idle test is capable of monitoring gross emitters; the basic idle testing is cost-effective and hence widely prevalent in developing countries, compared to the more sophisticated equipment used in the advanced tests; and that the idle mode emissions for CO and HC are high compared to those of other driving modes and idling as well as low-speed ranges occupy a large proportion of total driving time in urban areas.

In view of the advantages of idle testing, the I/M program framework in many developing countries still relies on idle (low or high) testing for in-use emission compliance by petrol-driven cars. Further, As NCT (National Capital Territory) of Delhi is characterized by several congested traffic intersections, the vehicles passed a substantial time of daily commuting in idling (15–20%). Therefore, both idle and fast idle tests were performed in the present study, even though the correlation between these two test results and emissions measured under more realistic driving conditions is poor (Pandey et al. 2016).

As part of the Indian I/M program, all in-use vehicles are required to mandatorily obtain a Pollution Under Control (PUC) certificate, which is issued based on successful compliance to idle emission values of CO and HC for petrol vehicles using auto-exhaust gas analyzers only at government-authorized centres (CPCB 2010). This system has several flaws and needs peculiar changes for better outcomes (Fig. 2.1).

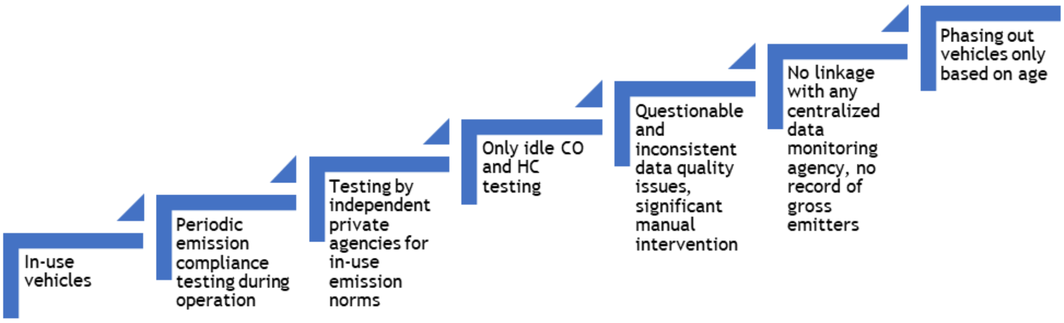


Fig. 2.1. Existing emission compliance testing framework for in-use cars

From literature review, it is found that there is a need to address the following gaps –

- Most of the studies have expressed the need to refine their findings (effect of vehicle variables on emission) with a larger, representative, and heterogeneous dataset.
- Studies attempting to conduct thorough in-situ analysis of tailpipe emission and vehicular traits regarding emission compliance testing (especially in developing countries) are highly required.
- Studies on the effect of progressive stringency of emission norms on vehicular emissions, particularly in-use vehicles are scantily available and need to be conducted to bring about more understanding
- As the in-use vehicles form a substantial portion of the overall vehicular fleet, an assessment of their actual emission vis-à-vis vehicle variables is required to ascertain the changes required in the existing I/M framework.

Therefore, the present study assessed the petrol-driven passenger cars appearing at PUC centres for emission recertification for their tailpipe parameters in a collaborated testing program. Based on the data analysis outcome, useful inferences indicate the need to strengthen the I/M program in developing countries.

2.2 Diesel-driven passenger cars

In the preceding 15 years span, worldwide passenger car sales have embraced a very high growth of 21.16 % and 17.97 % (year 2010 versus year 2019; and year 2005 versus year 2019, respectively) with African countries registering the lowest hike. A close look at the global passenger car sales' data between years 2005 and 2019 shows that it took just about 14 years interval to get the total sales figures of 45 million, doubled to 90 million (OICA 2019). However, there has been a worldwide dramatic shift from diesel-driven cars to gasoline or petrol / hybrid / electric-driven vehicles in the last few years. For example, in 2017, 6.77 million units of diesel cars were registered in Europe compared to 7.35 million units registered in 2016, showing a drop of 7.9 %, surpassing the lowest volume since 2013, when the European economy faced recession years. In 2018, the registration volume further shrunk to 5.59 million units only, recording just above 5.44 million marks witnessed since 2001.

In India, the situation is no different as the share of diesel cars dropped from about 47 % in 2012-13 to about 19 % in 2018-19 across various vehicle body types (JATO 2019). This change has been believed to be brought about by a mix of environmental (diesel cars are more polluting than their petrol counterparts) economical (once a wide gap between diesel and petrol fuel prices about a decade ago has almost been filled) and policy factors (the maximum allowable registration period of diesel cars is about half at 10 years compared to petrol cars with 15); Dieselgate in September 2015, having made the matter even worse (Mock 2018).

Despite diesel cars' sales declining over the last few years, their share in 'in-use vehicles' fleet remains substantial even considering privately-owned vehicles. This number of diesel cars is concentrated mostly in megacities compared to several other smaller urban areas and following so; such megacities emit a large fraction of global pollutants (Lawrence et al. 2007). The World Health Organization has estimated that increasing ambient air pollution has resulted in more than 4.2 million annual deaths along with various cases of respiratory illnesses in developing countries (WHO, 2019). Moreover, exposures to vehicular emissions (VE) have also been reported to trigger various health consequences including cardiovascular disease, pulmonary function decline, cancer and mortality (Ogunseye et al. 2018; Rice et al. 2015; Wong et al. 2019).

It is reported that over 70–80% of air pollution in megacities in developing nations is attributed to vehicular emissions caused by a large number of older vehicles coupled with poor vehicle maintenance, inadequate road infrastructure and low fuel quality (Badami, 2005; Singh et al. 2007; Wang et al. 2010; Pandey et al. 2016). The source of exhaust emissions (a mixture of gases and aerosols produced in the process of fuel combustion) is the engine, with carbon monoxide (CO), unburned or partly burned volatile hydrocarbons (HC), nitrogen oxides (NOx), sulphur oxides (SOx) and particulate matter (PM) being the main toxic components (Dobrzynska et al. 2020).

Although diesel engines are still a popular choice because of their advantages like higher thermal efficiency, better fuel economy and a higher degree of reliability over other engine types, however, they also, similar to other engines, tend to emit some harmful exhaust emissions, such as CO, unburned hydrocarbons HC, NO_X, SO_2 and smoke or PM (Sharma and Marechal, 2019). Usually, the NO_X and SE (smoke) are relatively higher in diesel engines compared to petrol engines (Alvarez et al. 2008; Karthikeyan and Prathima 2016). Besides human and plant lives, such emission has a direct adverse bearing on the environment (Bella and Venkateswar, 2010).

Several types of research have been carried out in the past to understand and mitigate harmful emissions from diesel vehicles in the form of technological advancements in engines and the adoption of emission control instruments (Basha et al. 2009; Sarvi and Zevenhoven 2010; Szybist et al. 2007; Ghazikhani et al. 2010; Squaiella et al. 2013).

An experimental study of the emission characteristics of diesel engines using direct and indirect injection combustion systems (DCS and ICS respectively) was carried out on the same model of two diesel engines fueled with diesel and the blend (diesel + Chinese pistache biodiesel). The smoke emissions from the ICS engine tested were significantly lower than that of DCS, especially for diesel fuel. For the ICS engine, the smoke reductions when using blend fuel are 26.8% and 31.7% on average compared to diesel (Huang et al. 2011). Similar extensive studies on biofuel, blended fuels, additives, and solvents having several combinations, with an aim to improve diesel engine's emission performance have been successfully carried out (El-Sessy et al. 2020; 2021; Razzaq et al. 2021).

Olabi et al. (2020) reported that the drivetrain technology of a diesel engine offers low CO_2 emissions due to its efficient combustion method as a byproduct of which more NO_X is produced, required to be neutralized in complex exhaust gas after-treatment processes for meeting a legally prescribed level. Further, the onset of technologies like Diesel Oxidation Catalyst (DOC) and Diesel Particulate Filter (DPF) has been useful in overcoming HCs, CO and SE challenges. Similar is the case of NOX through the advent of Selective Catalytic Reduction (SCR), NO_X storage catalysts (NSC), Ammonia Slip Catalyst (ASC) and Exhaust Gas Recirculation (EGR) techniques. However, as more stringent emission norms are being introduced worldwide, further minimization of these toxic pollutants from diesel vehicle's exhausts needs utmost research thrust.

The exhaust emissions from about fifty thousand road vehicles operating in London were monitored using roadside remote sensing tools (IR and UV), automatically retrieving vehicle-related information through sensors. Measurement of exhaust CO, HC, NO and SE were recorded in relation to vehicle category, fuel type and relevant Euro emission compliance norm. It was found that the smoke emission from light-duty commercial diesel cars reduced significantly in the transition from Euro 2 to Euro 3, and from Euro 3 to Euro 4. The study also confirmed that NO emission, however, was found to be statistically higher during the transition of Euro norm(s), highlighting the need to develop a sound understanding of the current and future 'in-use' emissions characteristics of diesel vehicles and their influence on local air quality (Rhys-Tyler et al. 2011).

As part of the Indian I/M program, all in-use diesel vehicles are required to obtain a Pollution Under Control (PUC) certificate mandatorily. This certificate is issued based on conformity of exhaust smoke emission standards while using free acceleration smoke testing and is required to be carried out using authenticated smoke meters only at government-authorized centres (CPCB 2010). This system does not have a uniform frequency of certification throughout the country; neither it takes into account other exhaust components, such as NOx or particle numbers for certification as a major drawback and moreover, the outcome emission data is not linked to any centralized I/M program identifying and keeping track of the gross emitters.

As regards to the research gaps, the following aspects are highlighted –

- Studies attempting to conduct thorough in-situ analysis of tailpipe (smoke) emissions and vehicular traits (especially in developing countries) are highly required.

- Studies on the effect of progressive stringency of emission norms on vehicular emissions, particularly in-use vehicles are scantily available and need to be conducted to bring about more understanding of the trend.
- Policy recommendations lack accuracy in identifying and phasing out cars that are the worst performers in terms of emission on account of age, mileage, and other vehicle-related variables.
- As the in-use vehicles form a substantial portion of the overall vehicular fleet, an assessment of their actual emission vis-à-vis vehicle variables is required to ascertain the changes required in the existing I/M framework, if any.

Therefore, in the present study, the diesel-driven passenger cars reporting at PUC centres for emission recertification subject to satisfactory smoke emission levels (HSU tested in FAST mode) were assessed for their tailpipe exhaust in a collaborated testing program spanning over half a year. Additionally, vehicle and engine-related variables were recorded along with ownership, existing PUC certificate and insurance validity verified through the government's relevant web portal.

The comprehensive emission testing schedule generated a larger and diverse dataset that was analyzed for two dataset scenarios, entire and top 5 makes, to explore the effect of the vehicle and selected engine-related aspects on smoke emission. In addition to the correlation findings using scatterplots, the concentration ranges of tailpipe parameters were also depicted through boxplots for a few vehicles and engine aspects. Further, an attempt was made to generate predictive emission equations for the diesel cars of the top 5 makes. Based on the data analysis outcomes, valuable inferences are drawn to strengthen the emission recertification and I/M program in relation to diesel-driven passenger cars.

2.3 Emission compliance

Governments, policymakers, and managers have been trying to strengthen various policy measures to improve urban air quality by maintaining ambient air pollution levels below the specified national and international standards. At-the-source control of vehicular pollution is among the most promising practices for pollution abatement, but this approach requires a very stringent administration system, policy revisits and re-strengthening, public awareness and support, and monitoring for implementation (Gulia et al. 2020).

As part of the Indian I/M program, all in-use vehicles are required to mandatorily obtain Pollution Under Control (PUC) certificate, which is issued based on conformity to idle emission test for petrol vehicles and is needed to be carried out using authenticated auto-exhaust gas analyzers only at government-authorized centres (CPCB, 2010). This system does not have a uniform frequency of certification throughout the country. Neither does it consider fast idle readings for certification as a major drawback. Moreover, the outcome emission data is not linked to any centralized I/M program identifying the gross emitters. The compliance evaluation of in-use LDVs (Light-Duty Vehicles) is a complex task without technical and financial support in many municipalities (Ventura et al. 2020), especially those in some other regions of developing countries (Dallman 2020).

Comparing the scenarios of emission certification policy in India versus the US, the PCVE (Programs to Control Vehicle Emissions) appears to be more effective because of the technical and legal framework put in place by the Environmental Protection Agency (USEPA), which is successful in implementation and compliance of the pertinent policies (Bandivadekar et al. 2015). Going forward, the other reason is the availability of the technical expertise and skilled resources with USEPA to analyse and confirm emission measurements and data reports presented by the manufacturers. As a result, the pass %age of LDVs through the designated laboratories is as low as 15% (He et al., 2017).

Moreover, in such vehicle inspection programs, the emission results are transparent and readily available to the public and have provisions for punishments and vehicle recalls (voluntarily or through the penal course), tax sanctions and compensation (Maxwell and Hannon 2017). Another peculiarity lies in the fact that apart from having more efficiency in the compliance by the new passenger cars, the testing structure of US PCVE lets in-use vehicles also be subject to inspection, repair, maintenance and durability requirements prescribed by the EPA (Mock and German 2015). Excluding some parts, the environmental policymakers in the European Union

(EU) and China are yet to have established re-testing programs (Mock and German 2015; Rodríguez et al. 2019).

In China, the government has also been affecting an inspection and maintenance system for the in-use vehicle to identify and eliminate relatively older vehicles (Lyu et al. 2020). On the other hand, the Brazilian regulators have found strong limitations as regards the in-use LDV's emission compliance programs (Dallman 2020). Both countries have necessitated the requirement of more stringent control norms with a more considerate and homogeneous emission compliance policy, especially in the areas reporting dramatic growth in LDV fleet (Ribeiro et al., 2021).

An investigation in India covering 300 petrol-driven passenger cars of Maruti make for their tailpipe emission compliance to the BS I and BS II norms found a very high compliance level to the former norm (over 80 %), however in the case of the later / newer norm, many vehicles disqualified with only 12 – 15 % compliance level achieved. A need to refine the assessment of compliance levels with a larger and diverse make-wise dataset was expressed (Pandey et al., 2016).

From the literature review, it is felt that except US, EU and other developed countries, China and Brazil, the emission certification policies for in-use passenger cars in most developing countries are struggling to meet the overall vehicular emission reduction goals. Due to the lack of a comprehensive exploratory analysis of exhaust emission compliance of the petrol and diesel-driven light-duty passenger cars to the in-use emission norms required covering a large and heterogeneous make-wise dataset.

Therefore, in the present study, the petrol and diesel-driven passenger cars appearing at PUC (Pollution Under Control) centres for emission recertification as part of overall environmental policy were assessed for their tailpipe parameters (CO and HC for petrol-driven passenger cars – PDPCs; and SE for diesel-driven passenger cars – DDPCs) in a collaborated testing program spanning over a year. Additionally, vehicle and engine-related variables were recorded along with ownership, existing PUC certificate and insurance validity verified through the relevant web resource.

The comprehensive emission testing schedule generated a larger dataset that was analyzed for three dataset scenarios, entire; top 3 / top 5; and top 16 / top 13 model-wise to explore the compliance levels to the extent possible. In addition to the compliance level evaluation, the effect of the vehicle's maintenance category and the emission norm (at manufacturing time) was also assessed during the present work. The compliance levels of tailpipe emission parameters were depicted through multiple bar charts and boxplots against in-use emission norms. Based on the data analysis outcomes, useful inferences are drawn to strengthen the emission recertification policy in relation to the in-use petrol and diesel-driven passenger cars.

2.4 Exhaust emission index (EEI)

The poor I/M infrastructure status in developing counties is also attributable to the high cost of next-generation instrumentation of emission testing devices. These are capable of accurately monitoring other important emission parameters, such as oxides of nitrogen (NO_X), particulate matter (PM), particle number concentration (PNC) both in-vitro (through laboratory tests under varying load conditions for e.g., using chassis dynamometer) and in-vivo (reflecting real-time driving conditions by using portable emission monitoring system or PEMS or remote sensing tools) and are finding place in emission testing and stringency of norms based on real driving emissions (RDE) in European countries Frey et al., 2010; Cao et al., 2016; Vlachos et al., 2014). There has been greater emphasis on collecting in-use emissions measurements from a wider range of vehicles and operating conditions (Yang et al., 2018).

However, the associated high cost toward set-up of advanced instruments, incorporation of RDE and implementation of upgrades in the existing I/M programs are the major bottlenecks in developing countries. Like many other countries, most Asian countries have taken various initiatives to implement an effective inspection and maintenance program (Dandapat et al., 2020). It is also seen that public awareness is poor as regards to the environmental and energy costs associated with their travel (Daher et al., 2018) and this awareness has been found to vary across several factors, such as age, education level, gender and economic status (Liao et al., 2015). The same happens to be the case with people's perception of what exactly it means to have an emission compliance certification is no more than the fact that they can now drive for one more year or so without being asked by the transport authorities for a valid certification document.

The emission norm and test values typically printed on the certificate document declaring a vehicle's fitness do not draw any particular attention of the commuters against the widely known AQI, which has now been gaining attention in developing countries as well. In India and many other developing countries, the I/M programs for in-use vehicles remain highly ineffective compared to the developed countered like the USA and other European countries (ICCT, 2013; Table 1).

Table 2.1 In-use vehicle I/M program status in developing and developed countries

I/M aspect	**Developing countries**	**USA / EU / Other developed countries**
Testing agencies	State / local authorities	Independent (private) operators
Emission measurement data quality assurance and test instrument	No uniformity, high degree of human intervention, poor calibration and upkeep of test instruments	Uniform, less human intervention, better handling and maintenance of test instruments
Linkage of testing data with vehicle registration	Not linked	Linked
Linkage of testing data with centralized system	Not linked / No identification of gross emitters	Linked / Identification of gross emitters
Testing feedback to manufacturer	Not provided	Provided
Certificate of Compliance	Issued to vehicle owner, no other identification	Visible sticker issued to the I/M compliant vehicles
Testing protocol	Basic/mass emission of only CO and HC in no-load idle/fast idle modes	Advanced / RDE testing using PEMS / load conditions
Recall policy	Not mandatory	Mandatory
Role of manufacturers in any ad-hoc/periodic emission testing/conformance	None	Yes, in the form of ICUP and ICVP (In-use verification program / confirmatory program)
I/M or PUC upgradation bottlenecks	Cost, public awareness, lack of an emission quality index even with the existing system	None as of now

Another problem is intra-vehicle assessment of tailpipe emission, for example, the CO value in tailpipe emission may be lower than the prescribed norm, but that of HC may be higher and vice-versa. In such case, a vehicle may be compliant for CO but non-compliant for HC and vice-versa too. It is, therefore, difficult to rationally declare the compliance or non-compliance of a vehicle in view of the prescribed in-use emission norm. In other words, the vehicle's 'pass' performance ascertained in the I/M testing will be questionably supported by the fact that over 80% of the vehicles come clear in such testing. Such emission compliance testing for in-use vehicles critically needs a tool that could indicate their emission performance in an easy-to-interpret statistical form (index) and suggest further courses of action that could render or keep them in a state of compliance with the relevant norms.

This very lack of a quick tool to indicate towards intra-vehicle assessment of compliance to 'in-use' emission norm is the theme of the present paper. In view of the above, the present study attempted to devise a unique approach to formulating the Exhaust Emission Index (EEI). As AQI can point towards ambient air quality in terms of a range of numerical values, each presenting an associated effect, EEI is conceptualized so that depending upon numerical values constructed analyzing tailpipe emission data of cars; a scale can be presented stating the emission-quality class or category of a vehicle. The EEI can be incorporated in the updated I/M program of developed countries as another line of action for emission recertification and/or phasing-out of a vehicle.

2.5 Concluding remarks

From the review of literature, it is evident that the study on how vehicle-related independent variables (including those related to the engine) affect the exhaust emission from both, the petrol and diesel-driven light-duty passenger cars is highly relevant and required. This requirement is further intensified by the fact that studies focusing on the exhaust emission from such cars, in respect of the fuel-specific, heterogenous fleet covering various makes and models plying on the urban roads of Delhi, are scantily available needing urgent attention. The effect of vehicular aspects (such as age, mileage, stringency of the emission norms, maintenance records, vehicle weight, transmission type, drivetrain type etc.) and various engine specifications (power, torque, cubic capacity, compression ratio, cylinder bore, piston stroke, aspiration type, number of cylinders, number of valve per cylinder, valve configuration and fuel mixing conditions etc.) on the tailpipe emission from light-duty passenger cars is one of the major thrust areas of research.

The comprehensive assessment of the compliance of cars towards in-use emission norms is also one of the grey areas pointing at the country's lenient approach toward the corresponding norms and other flaws making the I/M (Inspection and Maintenance) program less effective. Further, the emission compliance testing for in-use vehicles critically needs a tool that could indicate their emission performance in an easy-to-interpret statistical form (index) and suggest further course of action in what could render or keep them in a state of compliance with the relevant norms. It is, therefore, necessary to take up a study involving a large-scale and heterogeneous data acquisition and analysis programme for an in-situ exploratory assessment of tailpipe emissions from petrol and diesel-driven light-duty passenger cars in Delhi, India.

In the present work, in view of the limitations of time and resources, an attempt has been made to explore the effect of the vehicle and engine-related parameters on petrol and diesel passenger cars of various makes and models on their tailpipe CO, HC, CO_2, O_2, λ (Lambda) and AFR (Air Fuel Ratio) as well as the smoke emission (SE) under different testing conditions. The cars appearing for their periodic emission compliance testing against the in-use emission norms at various pollution under control (PUC) centres located across Delhi were tested for tailpipe emission under no-load stationary conditions.

The materials and methods, data collection and analysis, results and discussion, and important recommendations and conclusions have been presented in subsequent chapters.

CHAPTER 3

RESEARCH DESIGN AND METHODOLOGY

The present study concentrated on a sample size of 2040 passenger cars of different makes and models in the Indian national capital city. Both petrol and diesel-driven cars were attended to in the National Capital Territory (NCT) registered in the regional transport offices (RTOs) of various districts. Spread over 11 districts, NCT has a geographical area of approximately 1483 km^2 (Fig. 3.1). The capital city has almost every make and model of both indigenous and overseas car manufacturers, plying on its road. 1580 petrol-driven and 460 diesel-driven passenger cars were investigated for vehicle and engine-related parameters along with tailpipe emission characteristics or parameters.

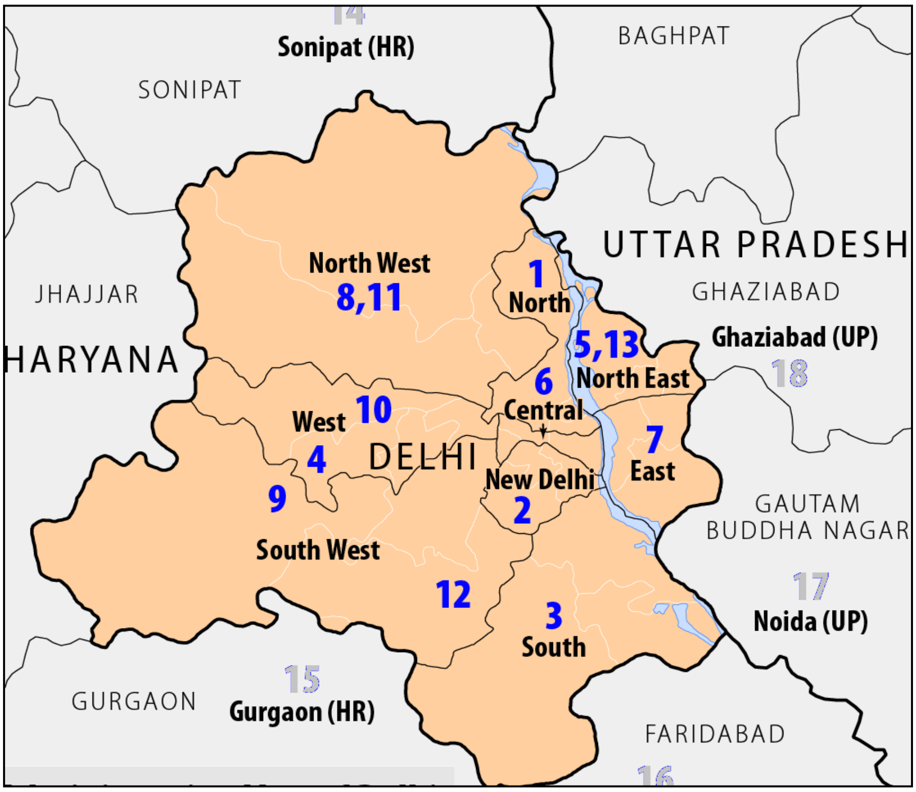


Fig. 3.1 Map of study area showing districts and RT offices

3.1 Emission testing program

The testing of vehicles was carried out in collaboration with a few PUC - Pollution Under Control (certification) centres located across various districts of the NCT. Only those PUCCs were selected that possessed a particular make and model of tailpipe exhaust gas and analyzer and smoke meter duly certified by ARAI (Automotive Research Association of India) under CMVR (Central Motor Vehicle Rules) prescribed by the Government of India (Table 3.1). This was done in order to maintain uniformity in instrumentation's operation, calibration, maintenance and any other associated requirements. The vehicle testing programme spanned over a period of 12-13 months, attending to about 2000 vehicles. On average, 4-6 vehicles were tested daily; however, only one PUC centre was engaged in testing at one point of time (no simultaneous operation). The vehicles reporting for PUC certificate were stopped at the PUC centre and tested for tailpipe emission in idle and fast idle conditions along with vehicle and engine-related parameters. Ownership, insurance, existing PUC certification details were also verified using the MoRTH (Ministry of Road Transport & Highways) web portal.

Table 3.1: List of PUCCs associated for vehicle testing program in Delhi

S. No.	**Agency name**	**Agency code / District (Zone)**	**Address**	**Districts / RTOs covered**
		Petrol-driven cars		
1	Scorpio Petro	P-723 / South-West	Community Center, Sector-18A, Dwarka, New Delhi-110045	South-West / South / West
2	B S Dwarka	P-679 / South-West	Sec-11, Dwarka, New Delhi - 110075	South-West / South / West
3	Bhargavi Auto Services	P-496 / West	Virendra Nagar, Janak Puri, Delhi-110058	West / South-West
4	Galaxy Automobiles Pvt. Ltd.	P-757 / South	F-84, Okhla Industrial Area, Phase – I, Delhi 110020	South / South-West
5	Narayan Service Station	P-683 / North	Mall Road, Khyber Pass, Delhi-110054	North / North-West / North-East / Shahdara
6	National Service Station	P-432 / New Delhi	H-Block , Connaught Circus, Connaught place, New Delhi - 110001	New Delhi / North / East / South / West / Shahdara
7	Ajay Service Station	P-719 / North-East	Petrol pump, G T Road, Dilshad Garden, Delhi -110095	North-East / North
8	Bagga Link	P-775 / Central	Near Hanuman statue, Link Road, Karol Bagh, New Delhi-110005	Central / New Delhi /

9	Deepak Motors	P-148 / East	Petrol Pump, Surya Nagar, Opposite. Vivek Vihar, Delhi-110095	East / North-East
Diesel-driven cars				
1	Scorpio Petro	D-379 / South-West	Community Center, Sector-18A, Dwarka, New Delhi-110045	South-West / South / West
2	B S Dwarka	D-304 / South-West	Sec-11, Dwarka, New Delhi -110075	South-West / South / West
3	Bhargavi Auto Services	D-298 / West	Virendra Nagar, Janak Puri, Delhi-110058	West / South-West
4	Galaxy Automobiles Pvt. Ltd.	D-411 / South	F-84, Okhla Industrial Area, Phase – I, Delhi 110020	South / South-West
5	Narayan Service Station	D-314 / North	Mall Road, Khyber Pass, Delhi-110054	North / North-West / North-East / Shahdara
6	National Service Station	D-498 / New Delhi	H-Block , Connaught Circus, Connaught place, New Delhi -110001	New Delhi / North / East / South / West / Shahdara
7	Ajay Service Station	D-374 / North-East	Petrol pump, G T Road, Dilshad Garden, Delhi -110095	North-East / North
8	Paras Auto Service	D-272 / Central	Asaf Ali Road, New Delhi-110002	Central / New Delhi /
9	Deepak Motors	D-103 / East	Petrol Pump, Surya Nagar, Opposite. Vivek Vihar, Delhi-110095	East / North-East

3.2 Sample characteristics (frequency analysis)

The emission testing program attended to 2040 number of light motor vehicles (LMVs) consisting of 1580 petrol-driven and 460 diesel-driven passenger cars registered in the jurisdiction of NCT of Delhi, India. District and RTO (concerned Regional Transport Office) wise distributions of all the cars are presented in Tables 3.2 – 3.5). Maximum number of cars tested belonged to South-West district and Dwarka RT office followed by the West district and Wazirpur and Rajouri Garden RT offices representing more than half of the total sample size (n = 2040). Interestingly, hatchback body type dominated the petrol cars (69.36 %) while the highest share of diesel cars was attributable to SUV (Sports Utility Vehicle) followed by hatchbacks with 39.44 % and 31.52 % numbers respectively (Table 3.6).

Table 3.2: District-wise sample frequencies for petrol cars

District	Frequency	%age	Cumulative %age
Central	47	2.975	2.975
East	41	2.595	5.570
New Delhi	140	8.861	14.430
North	77	4.873	19.304
North-East	17	1.076	20.380
North-West	225	14.241	34.620
South	125	7.911	42.532
South-West	587	37.152	79.684
West	321	20.316	100.000
Total	**1580**	**100.00**	

Table 3.3: District-wise sample frequencies for diesel cars

District	Frequency	%age	Cumulative %age
Central	10	2.174	2.174
East	10	2.174	4.348
New Delhi	47	10.217	14.565
North	43	9.348	23.913
North-East	5	1.087	25.000
North-West	78	16.957	41.957
South	33	7.174	49.130
South-West	140	30.435	79.565
West	94	20.435	100.000
Total	**460**	**100.00**	

Table 3.4: RTO-wise sample frequencies for petrol cars

Registering RTO	Frequency	%age	Cumulative %age
Burari	3	0.190	0.190
Dwarka	502	31.772	31.962
IP Estate	140	8.861	40.823
Janakpuri	115	7.278	48.101
Loni Road	26	1.139	49.241
Mall Road	73	4.620	53.861
Mayur Vihar	20	1.266	55.127

Rajouri Garden	206	13.038	68.165
Rohini	11	0.696	68.861
Sarai Kale Khan	47	2.975	71.835
Sheikh Sarai	125	7.911	79.747
Surajmal Vihar	21	1.329	81.076
Vasant Vihar	85	5.380	86.456
Wazirpur	214	13.544	100.000
Total	**1580**	**100.00**	

Table 3.5: RTO-wise sample frequencies for diesel cars

Registering RTO	**Frequency**	**%age**	**Cumulative %age**
Burari	15	3.261	3.261
Dwarka	108	23.478	26.739
IP Estate	47	10.217	36.957
Janakpuri	17	3.696	40.652
Loni Road	3	0.652	41.304
Mall Road	30	6.522	47.826
Mayur Vihar	5	1.087	48.913
Rajouri Garden	77	16.739	65.652
Rohini	6	1.304	66.957
Sarai Kale Khan	10	2.174	69.130
Sheikh Sarai	33	7.174	76.304
Surajmal Vihar	5	1.087	77.391
Vasant Vihar	32	6.957	84.348
Wazirpur	72	15.652	100.000
Total	**460**	**100.00**	

Table 3.6: Body type-wise sample frequencies of passenger cars

Body type		**Frequency**	**%age**		**Frequency**	**%age**
Hatchback	**Petrol-driven cars**	1096	69.367	**Diesel-driven cars**	145	31.522
SUV		71	4.494		181	39.348
Sedan		413	26.139		134	29.130
Total		**1580**	**100.00**		**460**	**100.00**

The sample of 2040 passenger cars was analyzed for the underlying makes and models separately based on powering fuel. As many as fifteen makes of petrol and twelve makes of diesel cars were investigated in the present study. MSIL make alone held about 46.52% of total numbers, followed by MHIL @ 24.11% and HCIL @ 12.98%. (Table 3.7). Together, these three makes constituted about 83.61% of the total petrol-driven car numbers being considered as the basis of study of top 3 makes. Diesel-driven car's case was somehow different, where the top 3 makes together could only represent about 57.82% of the total number of cars; hence, in this case, the top 5 makes were considered to raise the contribution to a modest 74.34% (Table 3.8).

Further, the study also looked into a model-wise scenario of both petrol and diesel cars in the entire sample. A total of sixty-six different models of petrol cars and forty-two different models of diesel cars were gone through during the emission monitoring program respectively. The fleet was dominated by MSIL in both types of cars followed by HMIL. MSIL had the maximum number of models with Alto, Baleno. Dzire, Swift and Wagon-R models having maximum number of petrol and diesel cars both in the whole dataset. Other dominant models were Grand i10, i10 and i20 (of HMIL make) and Amaze and City (of HCIL make) in petrol cars (Table 3.9). As shown in table 3.10, in diesel car's fleet, apart from MSIL and HMIL, models of MML, TKMPL and FIPL were considered (XUV 500, Scorpio; Fortuner; Ecosport and Figo models respectively).

Table 3.7: Make-wise sample frequencies for petrol cars

S. No.	Make	Country	Frequency	%age	Cumulative %age
1	Audi	Germany	1	0.063	0.063
2	FAIPL (Fiat)	Italy	1	0.063	0.127
3	FIPL (Ford)	USA	37	2.342	2.468
4	GMIPL (General Motors)	USA	25	1.582	4.051
5	HCIL (Honda)	Japan	205	12.975	17.025
6	HMIL (Hyundai)	South Korea	381	24.114	41.139
7	HML (Hindustan)	India	1	0.063	41.203
8	MML (Mahindra)	India	5	0.316	41.519
9	MSIL (Maruti)	India	735	46.519	88.038
10	NMIPL (Nissan)	Japan	7	0.443	88.481
11	RIPL (Renault)	France	25	1.582	90.063

12	SAIPL (Skoda)	Czech	9	0.570	90.633
13	TKMPL (Toyota)	Japan	56	3.544	94.177
14	TML (Tata)	India	51	3.228	97.405
15	VWIPL (Volkswagen)	Germany	41	2.595	100.000
	Total		**1580**	**100.00**	

Table 3.8: Make-wise sample frequencies for diesel cars

S. No.	Make	Country	Frequency	%age	Cumulative %age
1	FIPL (Ford)	USA	38	8.261	8.261
2	GMIPL (General Motors)	USA	12	2.609	10.870
3	HCIL (Honda)	Japan	38	8.261	19.130
4	HMIL (Hyundai)	South Korea	57	12.391	31.522
5	MBIPL (Mercedes)	Germany	5	1.087	32.609
6	MML (Mahindra)	India	54	11.739	44.348
7	MSIL (Maruti)	India	155	33.696	78.043
8	RIPL (Renault)	France	16	3.478	81.522
9	SAIPL (Skoda)	Czech	5	1.087	82.609
10	TKMPL (Toyota)	Japan	46	10.000	92.609
11	TML (Tata)	India	21	4.565	97.174
12	VWIPL (Volkswagen)	Germany	13	2.826	100.000
	Total		**1580**	**100.00**	

Based on representativeness in the entire fleet, the top sixteen models in the petrol car category and the top thirteen models in the diesel car category were selected for analysis and interpretation in the present study representing over 65% of the overall sample size.

Table 3.9: Model-wise sample frequencies for petrol cars

S. No.	Model	Frequency	%age	Cumulative %age
1	A-Star	4	0.253	0.253
2	A6	1	0.063	0.316
3	Alto	133	8.418	8.734
4	Amaze	65	4.114	12.848
5	Ameo	7	0.443	13.291
6	Aspire	3	0.190	13.481

7	BR-V	4	0.253	13.734
8	Baleno	90	5.696	19.430
9	Beat	12	0.759	20.190
10	Bolt	2	0.127	20.316
11	Brio	16	1.013	21.329
12	Camry	2	0.127	21.456
13	Celerio	35	2.215	23.671
14	Ciaz	31	1.962	25.633
15	City	85	5.380	31.013
16	Civic	3	0.190	31.203
17	Corolla Altis	8	0.506	31.709
18	Creta	29	1.835	33.544
19	Datsun Go	2	0.127	33.671
20	Duster	3	0.190	33.861
21	Dzire	110	6.962	40.823
22	Ecosport	9	0.570	41.392
23	Eeco	9	0.570	41.962
24	Eon	28	1.772	43.734
25	Ertiga	10	0.633	44.367
26	Esteem	1	0.063	44.430
27	Etios	30	1.899	46.329
28	Etios Liva	15	0.949	47.278
29	Fabia	5	0.316	47.595
30	Fiesta	2	0.127	47.722
31	Figo	22	1.392	49.114
32	Fortuner	1	0.063	49.177
33	Grand i10	55	3.481	52.658
34	Ignis	13	0.823	53.481
35	Ikon	1	0.063	53.544
36	Jazz	21	1.329	54.873
37	KUV 100	6	0.380	55.253
38	Kwid	22	1.392	56.646
39	Linea	1	0.063	56.709
40	M-800	3	0.190	56.899
41	Micra	4	0.253	57.152
42	Mobilio	1	0.063	57.215

43	Nano	8	0.506	57.722
44	Nexon	6	0.380	58.101
45	Omni	1	0.063	58.165
46	Polo	26	1.646	59.810
47	Rapid	4	0.253	60.063
48	Ritz	27	1.709	61.772
49	SX4	2	0.127	61.899
50	Sail	2	0.127	62.025
51	Santro	33	2.089	64.114
52	Spark	11	0.696	64.810
53	Sunny	1	0.063	64.873
54	Swift	147	9.304	74.177
55	Tiago	25	1.582	75.759
56	Tigor	7	0.443	76.203
57	Vento	8	0.506	76.709
58	Verna	17	1.076	77.785
59	WR-V	8	0.506	78.291
60	Wagon-R	106	6.709	85.000
61	Xcent	19	1.203	86.203
62	Zen	1	0.063	86.266
63	Zen Estilo	11	0.696	86.962
64	Zest	3	0.190	87.152
65	i10	107	6.772	93.924
66	i20	96	6.076	100.000
	Total	**1580**	**100.000**	

Table 3.10: Model-wise sample frequencies for diesel cars

S. No.	Model	Frequency	%age	Cumulative %age
1	Amaze	19	4.130	4.130
2	Baleno	1	0.217	4.348
3	Bolero	2	0.435	4.783
4	Brezza	26	5.652	10.435
5	CLA 200	5	1.087	11.522
6	Chevrolet Beat	9	1.957	13.478
7	Chevrolet Sail	3	0.652	14.130
8	Ciaz	18	3.913	18.043

9	City	13	2.826	20.870
10	Creta	11	2.391	23.261
11	Duster	16	3.478	26.739
12	Dzire	37	8.043	34.783
13	Ecosport	21	4.565	39.348
14	Endeavor	1	0.217	39.565
15	Ertiga	7	1.522	41.087
16	Etios	3	0.652	41.739
17	Etios Liva	14	3.043	44.783
18	Fabia	5	1.087	45.870
19	Figo	15	3.261	49.130
20	Fortuner	15	3.261	52.391
21	Grand i10	6	1.304	53.696
22	Indica Vista	5	1.087	54.783
23	Indigo CS	3	0.652	55.435
24	Innova	11	2.391	57.826
25	Innova Crysta	4	0.870	58.696
26	Mobilio	3	0.652	59.348
27	Nexon	5	1.087	60.435
28	Polo	6	1.304	61.739
29	Ritz	11	2.391	64.130
30	S-Cross	9	1.957	66.087
31	Scorpio	20	4.348	70.435
32	Sumo Grande	5	1.087	71.522
33	Swift	48	10.435	81.957
34	TUV 300	2	0.435	82.391
35	Vento	7	1.522	83.913
36	Verna	19	4.130	88.043
37	WR-V	3	0.652	88.696
38	XUV 500	23	5.000	93.696
39	Xcent	5	1.087	94.783
40	Xylo	6	1.304	96.087
41	Zest	2	0.435	96.522
42	i20	16	3.478	100.000
	Total	**460**	**100.000**	

3.3 Data collection during testing program

During the emission testing program across the NCT, various dependent and independent variables were recorded. The first independent variable set included vehicle-related parameters, whereas the second concentrated on engine-specific aspects. The dependent variable set comprised of tailpipe emission parameters. The details of different variables recorded are presented in Tables 3.11 and 3.12 for petrol and diesel-driven passenger cars respectively.

Table 3.11: Variables recorded during testing program for petrol cars

Item	Particulars	Unit / Specs.
Vehicle parameters	Make	-
	Model	-
	Body type	Hatchback / Sedan / SUV
	Age	Years
	Mileage	Kilometer (km)
	Kerb weight	Kilogram (kg)
	Status of registration life	Half-past (Yes / No)
	Emission norm (at manufacturing)	BS (Bharat Stage) I / II / III / IV
	Transmission type	Manual / Automatic
	Drivetrain type	FWD / RWD / AWD (4*4)
	Maintenance category	Very good / Good / Poor / Unsatisfactory
Engine parameters	Fuel	Petrol
	Capacity range	Cubic (cc)
	Stroke	4
	Maximum power	Brake Horse Power (bhp)
	Maximum torque	Newton Meter (Nm)
	Compression ratio (:1)	XX.X
	Cylinder bore	XX.X (mm)
	Piston stroke	XX.X (mm)
	Aspiration type	Natural / Turbo
	No. of cylinders	2 / 3 / 4
	No. of valves per cyliner	2 / 3 / 4
	Valve configuration	Single or Double Over-Head Cam (SOHC / DOHC)
	Fuel mixing condition	Rich / Lean / Stoichiometric
Exhaust emission variables	CO, CO_2 and O_2	Percent (%) volume
	HC	Parts per million (ppm) volume

	Lambda (λ) and AFR – measured	-
Other variables	Air:Fuel Ratio (AFR)	XX.XX
	Mixture conditions	Lean / Rich / Stoichiometric
Emission equation applied	Quadratic / Polynomial (Binomial)	2nd degree $y = ax^2 - bx + c$
Testing modes	Idle	CO and HC
	Fast Idle	CO, HC, CO_2, O_2, λ and AFR
RPM mesurements	Engine flywheel revolutions per minute in idle / fast idle conditions	As per manufacturers's recommndations / as recorded during testing until the readings stabilized

Table 3.12: Variables recorded during testing program for diesel cars

Item	**Particulars**	**Unit / Specs.**
Vehicle parameters	Make	-
	Model	-
	Body type	Hatchback / Sedan / SUV
	Age	Years
	Mileage	Kilometer (km)
	Kerb weight	Kilogram (kg)
	Status of registration life	Half-past (Yes / No)
	Emission norm (at manufacturing)	BS (Bharat Stage) II / III / IV
	Transmission type	Manual / Automatic
	Drivetrain type	FWD / RWD / AWD (4*4)
	Maintenance category	Very good / Good / Poor / Unsatisfactory
Engine parameters	Fuel	Diesel
	Capacity range	Cubic (cc)
	Stroke	4
	Maximum power	Brake Horse Power (bhp)
	Maximum torque	Newton Meter (Nm)
	Compression ratio (:1)	XX.X
	Cylinder bore	XX.X (mm)
	Piston stroke	XX.X (mm)
	Aspiration type	Natural / Turbo
	No. of cylinders	2 / 3 / 4
	No. of valves per cylinder	2 / 3 / 4
	Valve configuration	Single or Double Over-Head Cam (SOHC / DOHC)
	Fuel distribution system	DI / CDRI / PGM - FI

Exhaust emission variables	HSU	Number
Emission equation applied	Quadratic / Polynomial (Binomial)	2nd degree $y = ax^2 - bx + c$
Testing modes	Free Acceleration Smoke Test (FAST)	Smoke density (HSU)
RPM mesurements	Engine flywheel revolutions per minute in minimum ans maximum test conditions	As per MoRTH's guidelines of FAST / as recorded during testing until the readings stabilized

The literature review has found that the vehicles, once put to on-road operation after their registration, tend to emit more pollutants compared to emission certification levels during sales (or just after coming out of plant post-manufacturing). This is largely attributed to a combination of various factors, such as wear and tear, poor degree of inspection and / or maintenance, history of engine faults, vehicle age, mileage, driver's behavior, quality of fuel etc. as the most significant ones (Pandey et al., 2016).

Although the exponentially growing number of vehicles worldwide and specially in developing countries is directly related to the overall mass vehicular emission, it is also of paramount importance to put forward a rather qualitative study of tailpipe emission characteristics to understand as to how vehicle and engine-related parameters affect a vehicle's performance towards compliance to emission norms. The need for a larger dataset is often felt given the overall (very) high number of vehicles in the fleet in any geographical condition.

The government policies in curbing the high levels of vehicular emission are reflected in terms of vehicle emission performance assessment or the emission certification system or more commonly known as the inspection and maintenance (I/M) program(s). Irrespective of more and more emission norms being introduced globally, compelling automobile manufacturers to produce more environmentally benign vehicles, vehicular emissions are on the rise contributing to over 60% of air pollution globally. Hence, there is a need to refine the I/M program enabling the identification of emission behaviors of vehicles in response to vehicle and engine-specific parameters.

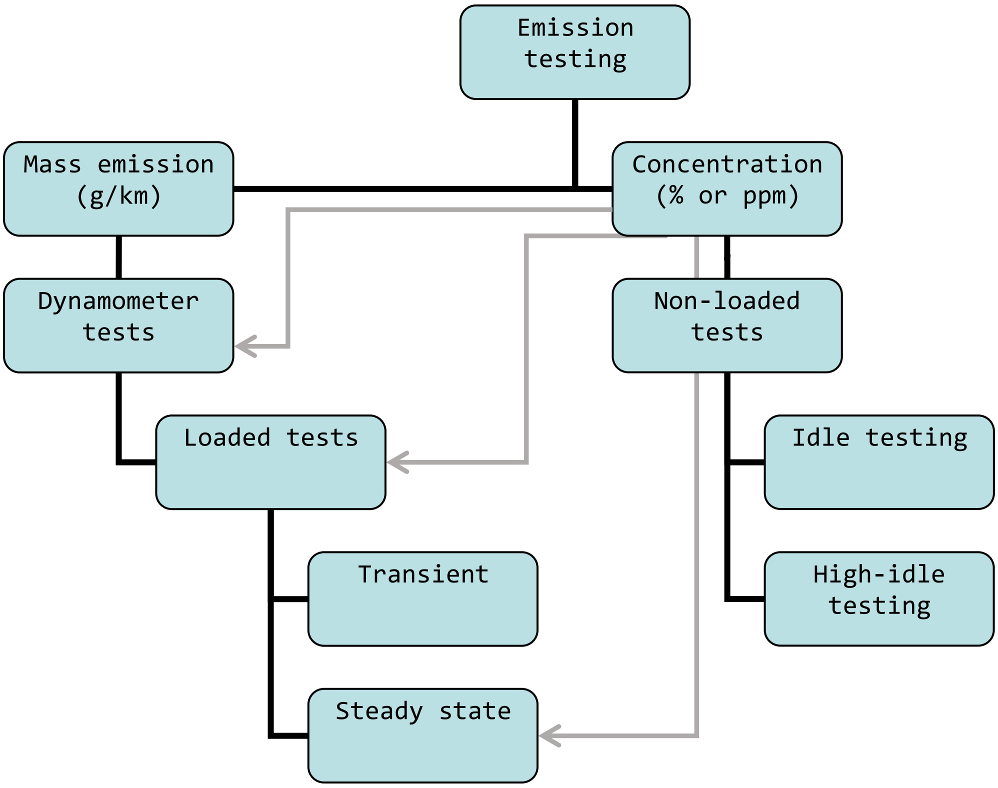


Fig. 3.2: Schematic diagram of I/M Test Types

I/M programmes, in most cases, have two types of emission testing, e.g., basic and advanced (Fig. 3.2). The most common being the measurement of CO and HC concentrations in the exhaust while the vehicle has been idling. The idle test was originally developed for vehicles with little or no emission control, and for these vehicles, it can detect a large proportion of malfunctioning or maladjusted engines. To help reduce the false failures with the idle test, some I/M programs require pre-conditioning at 2500 revolutions per minute (rpm) with no load for 3 minutes before a final idle test failure determination is made.

Various researchers have analyzed and reported high idling condition tests for the vehicles under no-load, in certain cases prior to the idling tests for stabilized concentration readings in the tailpipe. More vehicles were found to comply with emission test approval requisite after extended pre-conditioning. It was also observed that CO and HC emissions in the idle mode were higher than the fast-idle mode and these data were found to be consistent with data obtained by Kazopoulo et al. (2005) and Pandey et al. (2016).

However, no-load idling or fast idling tests do not account for acceleration and deceleration and do not put the engine under load. In fact, HC and NO_X emissions can be greatly affected by load and driving behavior. Moreover, significant amounts of NO_X are only created when a vehicle is under load as such, a loaded test is especially necessary to identify NO_x problems. On the other hand, advanced tests require a vehicle to simulate more rigorous driving conditions on a dynamometer under a loading similar to that which the vehicle would experience in actual driving. One such most recommended for use in I/M programs in the United States is the IM240 test. This 240-s test simulates vehicle operation under a variety of speed and acceleration conditions designed to mimic everyday urban driving.

However, the idle tests have some advantages over the others:

- Idle test is capable of monitoring gross emitters.
- The basic idle test uses comparatively cheap equipment, which is adoptable even with the lack of technical know-how to operate more sophisticated equipment as in the advanced tests.
- Idle mode emissions for CO and HC are high compared to those of other driving modes and idling as well as low speed ranges occupy a large proportion of total driving time in urban areas.

In view of the advantages offered by idle testing, the I/M program framework in many countries still relies on idle (low or high) testing for in-use emission compliance by petrol-driven cars and snap or free-smoke acceleration testing for that by diesel-driven passenger cars.

Table 3.13: In-use emission norms for a few developing countries

Country	**Vehicle registration particulars**	**Tailpipe emission parameter**			**Vehicle registration particulars**
		CO (%)	**HC (ppm)**	**HSU / K-Factor**	
Sri Lanka	Petrol vehicles other than motorcycles & motor tricycles	3.0	1000	-	Both Idling and 2500 RPM / no load
	Diesel vehicles	-	-	4.0	Snap acceleration
India	BS IV-compliant petrol cars	0.3	200	50	Idling & fast idling both / no load for
	Petrol cars other than BS IV-	0.5	-	65	

	compliant				petrol cars; Fast acceleration smoke test (FAST) for diesel cars
Thailand	Registered since Nov 1 1993	1.5	200		Engine idling / no load for petrol cars; 45% opacity and 50% filter paper (without load)
	Registered since Jan 1 2007	0.5	100		
Philippines	Registered for the first time after December 31, 2007	0.5	250	2.0	Idling / no load for petrol cars; Fast acceleration smoke test (FAST) for diesel cars
	Registered for the first time on or after 01 January 2003 but before January 1, 2008	3.5	600	2.5	
Canada	1998 and later	0.7	150	2.0	2-speed idle testing for petrol cars (as per EPA short I/M protocol); FAST for diesel cars
	1988 - 1997	1	200	-	

Considering the aforementioned advantages of the basic idle test, both idle and fast idle tests were performed in the present study for petrol cars and FAST for diesel cars, even though the correlation between these two test results and emissions measured under more realistic driving conditions is poor. After the selection of the testing methods for both types of passenger cars, a total of 2040 vehicles distributed across model years ranging between 1996 and 2019 were tested. This sample size is thought to be a fair representation of the passenger car fleet in the NCT of Delhi, having covered several makes and models (mostly considering sales as the criteria). The overall methodology is presented in Fig. 3.3 entailing the flow of the research works.

A four (4)-gas analyzer of Ozone make (model number Oz-Gas-04, manufactured in India by M/s Ozone Electronics Private Limited) was used to measure volumetric / mass concentrations of tailpipe emission parameters, i.e., CO, CO_2, O_2 (in % terms); HC (in ppm terms) and λ (as a dimensionless entity). The instrument was used in both idle and fast idling test conditions having an hardeware interface to measure idling and fast idling engine RPM also. Further, a smoke meter of the same make (model no. Oz-Gas-04) was deployed to measure smoke emitted by diesel vehicles (in HSU terms). Similar to 4-gas analyzer, the smoke meter also had a hand-held digital tachometer for engine RPM measurement. The particulars of both testing instruments are provided in Tables 3.13 and 3.14.

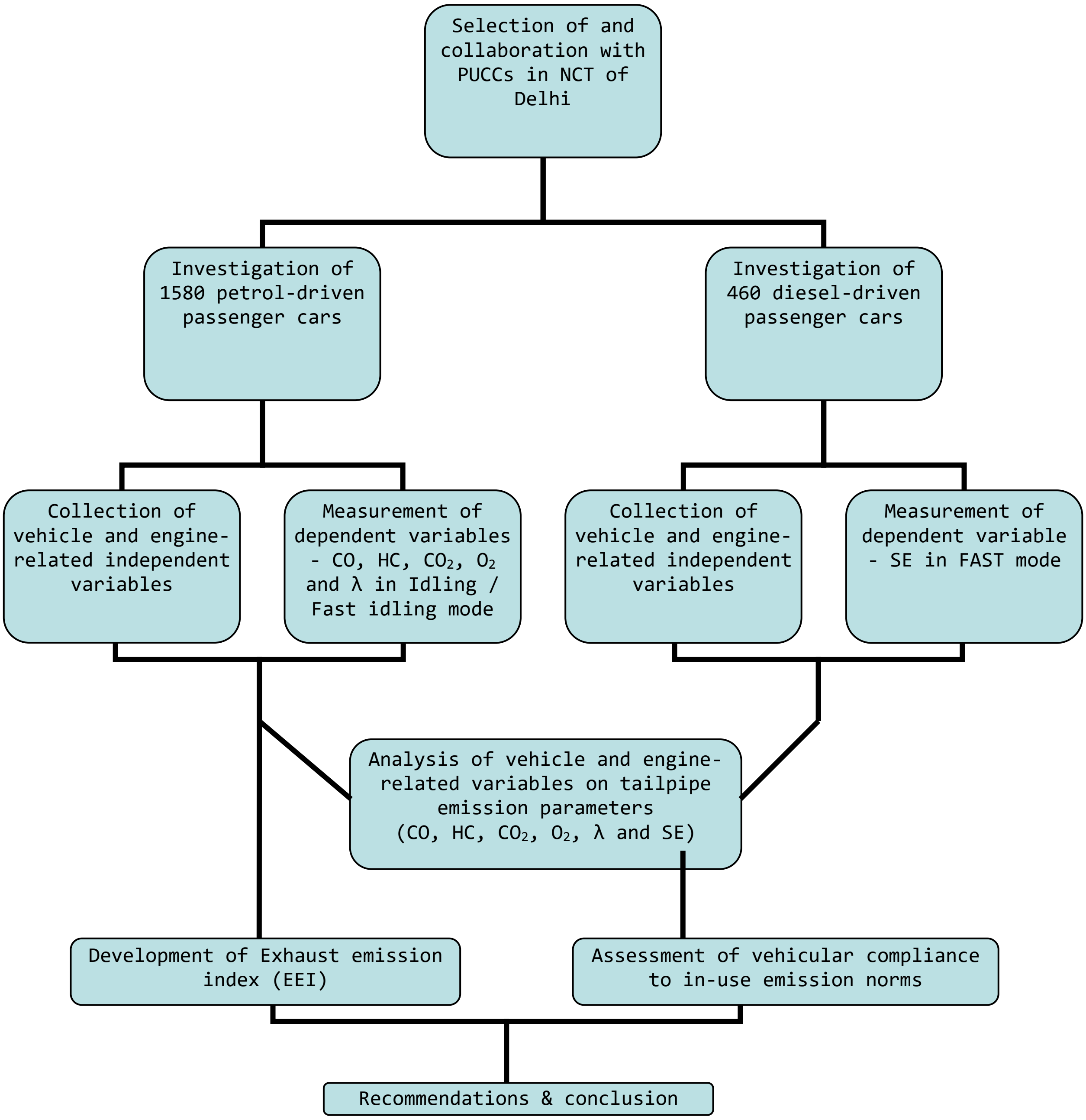


Fig. 3.3: Methodology of the study

Table 3.13: Field Instrument characteristics – 4-gas analyzer for petrol-driven cars

Item	**Particulars**
Make / Model	Ozone / Oz-Gas-05
ARAI approval (type-tested)	Yes
Government's approval for	Yes

application at / by PUCCs	Verified on – https://vahan.parivahan.gov.in/puc/views/ARAIApprovedEquipment.xhtml
Constituents measured	CO (Carbon Monoxide) / Carbon Dioxide (CO_2) / Hydrocarbon (HC), Oxygen (O_2) / AFR / (Lambda / λ)
Measurement type	Volumetric concentration
Measurement range	CO – 0-15 %; CO_2 – 0.01 %; HC – 1 ppm; O_2 – 0.01 %
Measurement resolution	CO – 0.001 %; CO_2 – 0-20 %; HC – 0-30,000 ppm; O_2 – 0-25 %
Principal of operation	CO / CO_2 / HC – NDIR (Non-Dispersive InfraRed) O_2 – ECS (Electro-chemical Sensor / Server)
Operating temperature (^{0}C)	4 – 45
RPM measurement range	400 – 9,999
Unit weight (kg)	7.5 (approx.)
Unit dimensions	344 x 368 x 223 mm (L x W x H)
Photo	

Table 3.14: Field Instrument characteristics – smoke meter for diesel-driven cars

Item	**Particulars**
Make / Model	Oz-Smoke-02
ARAI approval (type-tested)	Yes
Government's approval for application at / by PUCCs	Yes Verified on – https://vahan.parivahan.gov.in/puc/views/ARAIApprovedEquipment.xhtml
Constituents measured	Smoke density (Hartridge Smoke Unit)
Measurement type	Density / Opacity
Measurement range	Smoke density (HSU) – 0-100
Measurement resolution	Smoke density (HSU) – 0.01

Principal of operation	Attenuation of light beam based on Hartridge Geometry
Operating temperature (^{0}C)	4 – 45
RPM measurement range	400 – 9,999
Unit weight (kg)	10.5 (approx.)
Unit dimensions	Control Unit: 362 x 132 x 263 mm Measuring unit: 160 x 164 x 166 mm
Photo	

Only those PUC centres were selected for tailpipe emission monitoring which possessed Ozone make instruments as described in-here for petrol and diesel cars. Both the instruments / analyzers were checked for factory calibration prior to the commencement of the program, ensuring their ‘fit for usage’ status. The analyzers were facilitated with manual-zero calibration mode and were zeroed before and after each idle and fast idle measurement by placing the sampling probe about 2 m above the floor and away from the exhaust pipe or chemical fumes to establish a base set of gas ratios before testing.

Following zeroing, the sampling probe was inserted into the vehicle’s exhaust pipe up to a horizontal depth of 300 mm (or 10 inches) to ensure that the vehicle’s exhaust system and the sampling probe itself were leakage-free. Since all the vehicles were provided with a single exhaust pipe, no provision was made for the testing dual-pipe exhaust system. The instruments were equipped with a moisture sensor and filter to be able to eliminate it and, therefore, any possible error that might occur in readings. The concentration data for each vehicle was immediately printed in the form of a copy of the PUC (pollution under control) certificate and stored. This methodology was adopted at every single PUC centre and an emission testing program spanning over 13 months was accomplished, catering to 2,040 vehicles.

3.4 Data analysis tools

Considering the large volume of data, number of variables collected during the course of the emission testing program and objectives of the research, SPSS package (IBM SPSS Statistics, version 23) and OriginPro program (version 2021) were primarily used for the emission data analysis and presentation. The rationale behind the use of SPSS and OrigonPro lies in the fact that both the programs are easy to handle and capable to operate on a large dataset supported by their in-built simulation platform. The user interface is non-cluttered and tidy while plotting a graph. The data, once ready in the appropriate fashion in the data file / syntax in SPSS or in OriginPro, can be analyzed, transformed to present a characteristic trend amongst different dependent / independent variables collected during the tailpipe emission measurement. Further, the output of analysis can be obtained through graphical representation being able to be exported in various common formats of word processing (e.g., MS-Word).

SPSS and OriginPro being capable of quantitative and qualitative data analysis, are extensively used in conducting descriptive statistics, regression analysis, plotting different types of graphs, data transformation, analysis of variance (ANOVA), ‘t’ tests, tests of normality, non-parametric tests, linear modeling, forecasting etc. Required features were used in the present study to the extent of data analysis and interpretation. A few images showing SPSS and OriginPro window or user interfaces are depicted in Figs. 3.3, 3.4 and 3.5. MS-Excel was intermittently used for short-term data processing or storing some input data required for analysis in SPSS (for e.g., Bland-Altman plots). Excel was also used to maintain the master data files separately for petrol and diesel cars and EEI plotting.

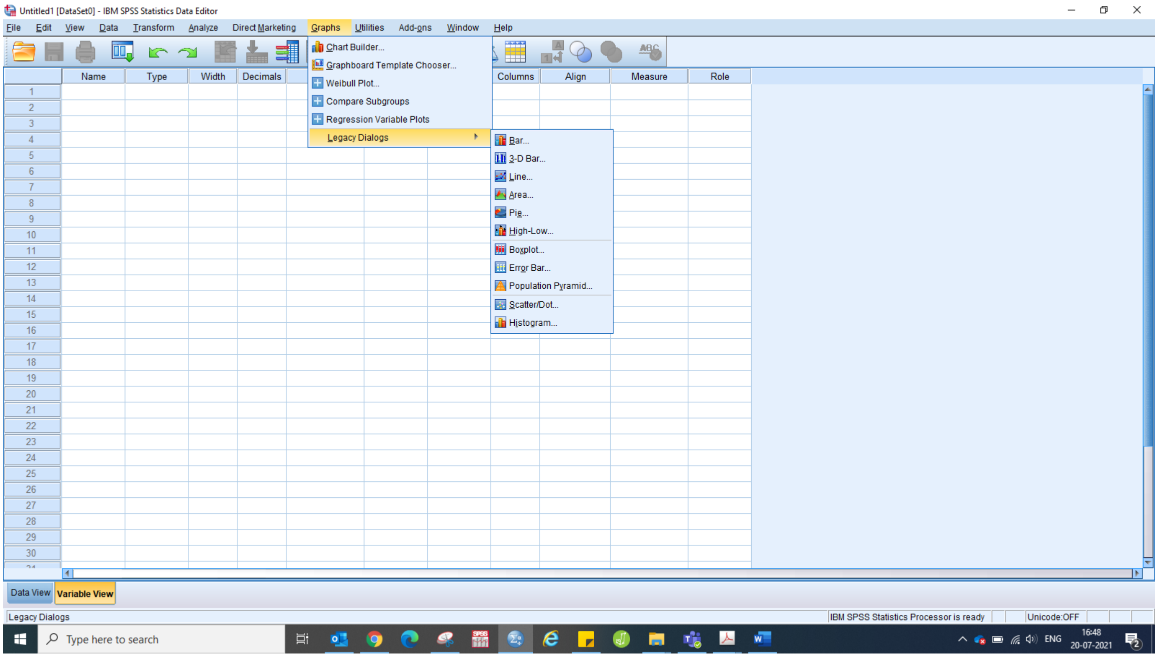


Fig. 3.3: SPSS user interface window for graphs

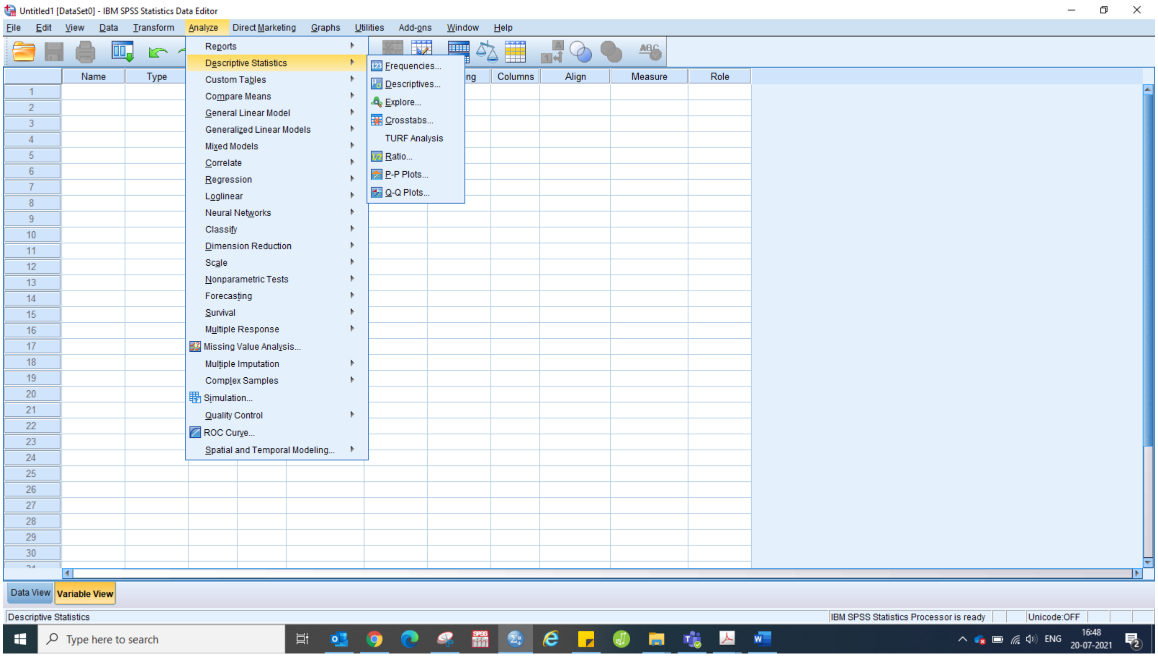


Fig. 3.4: SPSS user interface window for descriptive statistics

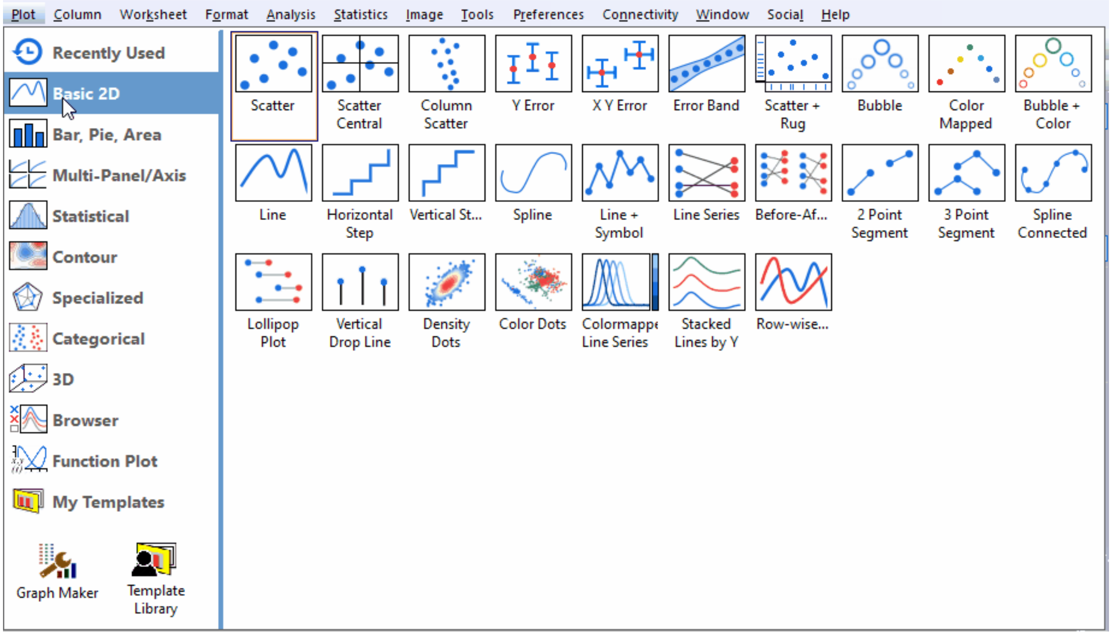


Fig. 3.5: OriginPro user interface window for graphs

Any visual error in the dataset was manually corrected prior to conducting the analysis in the SPSS package. The vehicle-related data was cross-checked at MoRTH's Vaahan web portal and engine data was double checked with web resources available with each make of the vehicle. Eventually, data analysis was carried out in view of the objectives of the research as outlined below.

- Review of literature to ascertain the recent findings in the area of tailpipe emission, important vehicle-related parameters and methodologies of the measurement of the emissions from both petrol and diesel-driven passenger cars, including research gaps.
- To quantify / characterize and investigate the effect of vehicle-related parameters, such as age, mileage, stringency (or progression) of the emission norms, maintenance records (i.e., I/M – Inspection and Maintenance), vehicle weight, transmission type, drivetrain type etc. on tailpipe emission parameters, such as, CO, HC, CO_2, O_2, λ (Lambda) and AFR (Air Fuel Ratio) as well as the smoke emission (SE).
- To quantify / characterize and investigate the effect of various engine-related variables, namely, power, torque, cubic capacity, compression ratio, cylinder bore, piston stroke, aspiration type, number of cylinders, number of valves per cylinder, valve configuration and fuel mixing conditions etc. on CO, HC, CO_2, O_2, λ and AFR as well as SE.

- Comprehensive assessment of the compliance of petrol and diesel-driven cars towards the in-use emission norms.
- Development of Exhaust Emission Index (EEI) for petrol-driven passenger cars using the emission data collected (CO and HC).
- To suggest changes in the extant emission regulation policy and in I/M programs to improve its efficiency.
- Suggestions relating to the control of tailpipe emission with reference to the in-use vehicle emission norms and classification criteria of vehicles on the basis of EEI.

CHAPTER 4

RESULTS AND DISCUSSION

In order to investigate the likelihood of effect of various vehicle and engine-related parameters on the tailpipe emissions, the data collected during the field measurements conducted at PUC (Pollution Under Control) test centres located across different districts of Delhi, India covering petrol and diesel-driven passenger cars of various makes and models are analyzed hereafter. As the emission measurement for the present study was done in collaboration with various PUC centres located across Delhi city, only those parameters were collected which form the basis of checking and issuing PUC certificates, for e.g.,

- For petrol-driven passenger cars = CO (Carbon Monoxide), HC (Hydrocarbon), CO_2 (Carbon Dioxide), O_2 (Oxygen), λ (Lambda), and AFR (Air:Fuel Ratio)
- For diesel-driven passenger cars = SE (Smoke Emission)

Considering the applicability of two testing methods, namely, idle and fast idle tests, volumetric concentrations of CO, HC (in both idling and fast idling modes) and CO_2, O_2, λ, and AFR – only in fast idling mode, were measured. On the other hand, SE was measured in HSU (Hartridge Smoke Unit) terms under FAST (Free Acceleration Smoke Test) method for diesel-driven cars which is considered as a proxy for particle measurement in diesel exhaust. Such measured values were plotted in relation to vehicle-related parameters, such as, vehicle age, vehicle mileage, body type, status of registration life half-past, kerb weight, transmission type, drivetrain type, applicable emission norm (at manufacturing) and maintenance category based on no. of fitness visits to manufacturer’s authorized service centres.

The variations in CO & HC were plotted under the two testing methods while HSU was plotted in only one mode (i.e., FAST). Further, the effects of engine-related aspects, namely, cubic capacity, maximum power, maximum torque, compression ratio, cylinder bore, piston stroke, aspiration type, no. of cylinders, no. of valves per cylinder, valve configuration and fuel mixing conditions were also plotted. In order to have a better resolution and understanding of vehicle’s performance towards tailpipe exhaust emission, the data analysis was carried out for the top 3 makes and top 16 models, representing 83.61% and 70.57% of the sample size (n = 1580). However, for diesel cars, the top 5 makes and top 13 models were taken up having represented the sample size (n = 460) in the best possible way (constituting 76.08 % and 63.7% respectively).

The average characteristics or range of the variables collected during the emission testing program for petrol and diesel-driven passenger cars are presented in Tables 4.1 and 4.2. All the makes and models of cars studied had four-stroke (4-S) engines, spark ignition system in the case of petrol cars and compression ignition in the instance of diesel cars respectively. All cars were found to be fitted with 3-way catalytic converters in satisfactory visual conditions. The tightening in registration norms (maximum 15 years for petrol cars and 10 years for diesel cars from the data of registration) reflected in the age of cars with only 3 cars violating this norm. Petrol cars tested were usually newer (average age < 4.5 years). MSIL make has the largest chuck of market share with its models also leading the sales in relevant vehicle class.

Table 4.1: Vehicle and engine characteristics for petrol cars

Item	**Particulars**
Vehicles	
Total numbers	1580
Fuel distribution type	MPFI (Multi-Point Fuel Injection)
Manufacturing date range	04-03-1999 to 27-12-2018
Vehicle age range (years)	0.01 – 20.04
Average age (years)	4.37
Oldest vehicle tested	M-800 (MSIL)
Newest vehicle tested	Baleno (MSIL)
Vehicle mileage range (km)	110 – 2,00,356
Average mileage (km)	45,605
Vehicle with highest mileage	M-800 (MSIL)
Vehicle with lowest mileage (km)	Baleno (MSIL)
No. of vehicles with registration life of 15 years over	3
No. of vehicles with registration life halfway past	255
Kerb weight range (kg)	635 – 1855
Top grosser make	MSIL (n = 735)
Top grosser model	Swift (n = 147)
Top three makes	MSIL / HMIL (n = 381) / HCIL (n = 205)
Top sixteen models	Alto (n = 133) / Amaze (n = 65) / Baleno (n = 90) / Celerio (n = 35) / City (n = 85) / Dzire (n = 110) /

	Eeco (n = 9) / Grand i10 (n = 55) / i10 (n = 107) / i20 (n = 96) / Jazz (n = 21) / Nexon (n = 6) Santro (n = 33) / Swift (n = 147) / Verna (n = 17) / Wagon-R (n = 106)
Engines	
Capacity range (cc)	624 – 2694
Stroke	4 (Four)
Maximum power range (bhp)	35 – 187.8
Maximum torque range (Nm)	51 – 320
Compression ratio range	8.8:1 – 17.6:1
Cylinder bore range (mm) / Piston stroke range (mm)	66 – 95 / 77 – 103.6
No. of cylinders (range)	2 – 4
No. of valves per cylinder (range)	2 – 4

Diesel cars had an average age of 4.51 years, slightly older compared to petrol cars. Age of diesel cars fell in line with the concerned registration norms. HMIL followed MSIL in terms of market size, yet far from being closer to its peer. Diesel cars were found heavier (kerb weight > 2.5 tons in certain cases) with no make or model having less than 3 cylinders. Fuel distribution or burning techniques were at par with the latest trends (petrol cars with MPFI and diesel cars having DI / CRDI technologies). Maximum diesel cars were fitted with turbo-charging system, a meagre in case of petrol cars. Automatic transmission seemed to be picking up as per market / sales trends, however, not evident in the samples attended to in the present study.

Table 4.2: Vehicle and engine characteristics for diesel cars

Item	Particulars
Vehicles	
Total numbers	460
Fuel distribution type	CRDI (Common Rail Direct Injection) / DI (Direct Injection) / PGM-FI (Programmed Fuel Injection)
Manufacturing date range	04-03-1999 to 27-12-2018
Vehicle age range (years)	0.05 – 10.38
Average age (years)	4.51
Oldest vehicle tested	Xylo (MML)
Newest vehicle tested	Brezza (MSIL) and Creta (HMIL)
Vehicle mileage range (km)	557 – 1,64,616
Average mileage (km)	56,241
Vehicle with highest mileage	Xylo (MML)
Vehicle with lowest mileage (km)	Creta (HMIL)
No. of vehicles with registration life of 10 years over	2

No. of vehicles with registration life halfway past	192 (41.74 % of sample size)
Kerb weight range (kg)	910 – 2510
Top grosser make	MSIL (n = 155)
Top grosser model	Swift (n = 48)
Top five makes	MSIL / HMIL (n = 57) / FIPL (n = 38) / MML (n = 54) / TKMPL (n = 46)
Top thirteen models	Amaze (n = 19) / Brezza (n = 26) / Ciaz (n = 18) / Duster (n = 16) / Dzire (n = 37) / Ecosport (n = 21) / Figo (n = 15) / Fortuner (n = 15) / i20 (n = 16) / Scorpio (n = 20) / Verna (n = 19) / XUV 500 (n = 23)
Engines	
Capacity range (cc)	936 – 2982
Stroke	4 (Four)
Maximum power range (bhp)	56.3 – 169
Maximum torque range (Nm)	138.4 – 380
Compression ratio range	10.3:1 – 18.5:1
Cylinder bore range (mm) / Piston stroke range (mm)	69.6 – 92 / 67.5 – 103.6
No. of cylinders	3 – 4
No. of valves per cyliner	2 – 4

4.1 Effect of vehicle and engine-related variables on tailpipe emission / parameters

A total of 1580 petrol-driven passengers cars falling in LMV (light motor vehicles) category were monitored for tailpipe emission and other parameters. The sampling characteristics have already been detailed in chapter 3 along with frequency tables showing make and model-wise scenarios. In-total, 15 makes and 66 models underwent the emission monitoring program. Based on representativeness in the sample, top 3 makes and top 16 models were also analyzed for various statistical conditions. Similarly, a total of 460 diesel-driven passenger cars belonging to LMV category were attended to in the vehicle testing schedule. Tailpipe emission and other parameters were collected and analyzed for top 5 makes and top 13 models also in addition to the entire dataset.

4.1.1 Petrol-driven passenger cars

4.1.1.1 Vehicle age

The effect of vehicle age on CO emission for the entire data range in both idle and fast idle testing modes is shown in Figure 4.1 and the same on HC emission is shown in Figure 4.2. It is revealed that the emission characteristics for both the parameters are best described by a 2nd order polynomial curve even though some scatter in data is conspicuous. The effect of vehicle age on other tailpipe emission parameters, i.e., CO_2, O_2, Lambda (λ) and AFR was also plotted. This depiction was done only for fast idling mode keeping in view the study protocol. CO_2 and O_2 emissions along with Lambda (λ) and Air:Fuel Ratio (AFR) for the entire data range are shown in Figures 4.3 and 4.4 respectively. It is revealed that Lambda (λ – calculated) and AFR-c (calculated) show a fairly good correlation with vehicle age implying that both reduce with aging vehicles.

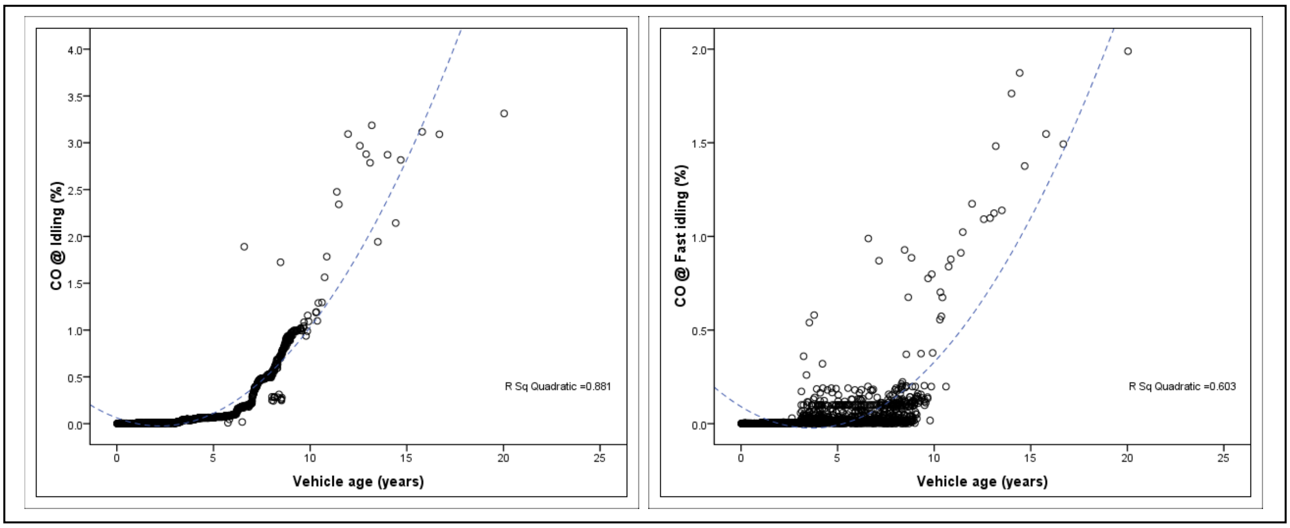


Fig. 4.1 Vehicle age vs. CO emission (at idling and fast idling)

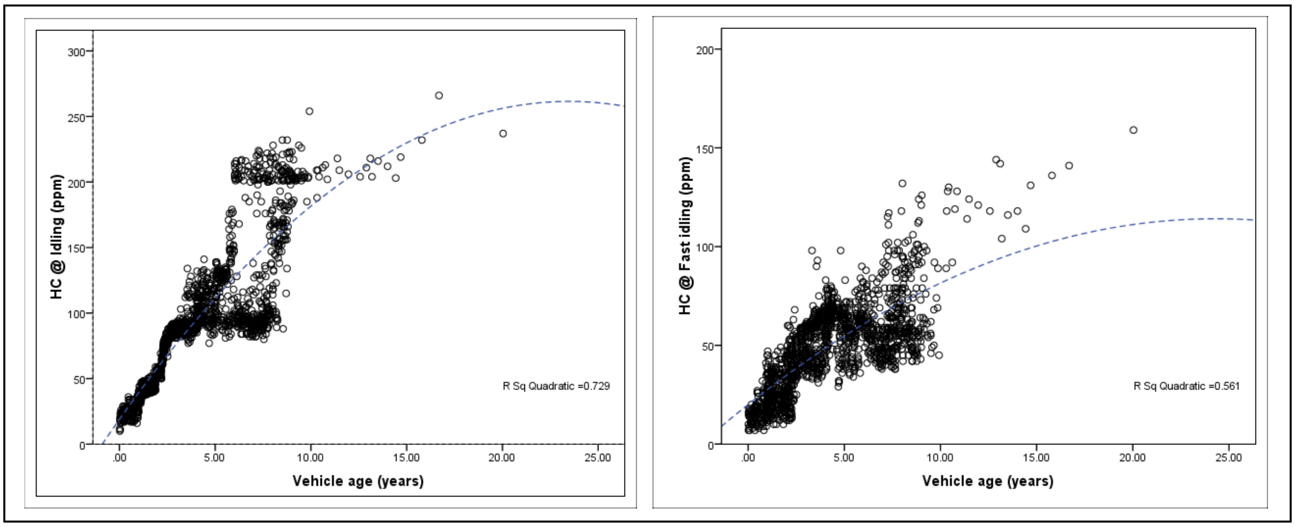


Fig. 4.2 Vehicle age vs. HC emission (at idling and fast idling)

On the other hand, the other two parameters, i.e., CO_2 and O_2 emissions were found not related to the vehicle age with R^2 values being too low pointing to virtually no correlation. The emission equations along with corresponding R^2 values computed using 2nd order polynomial curve presenting likelihood of correlation amongst all eight parameters with respect to vehicle age for idle and fast idle test methods are given in Table 4.3.

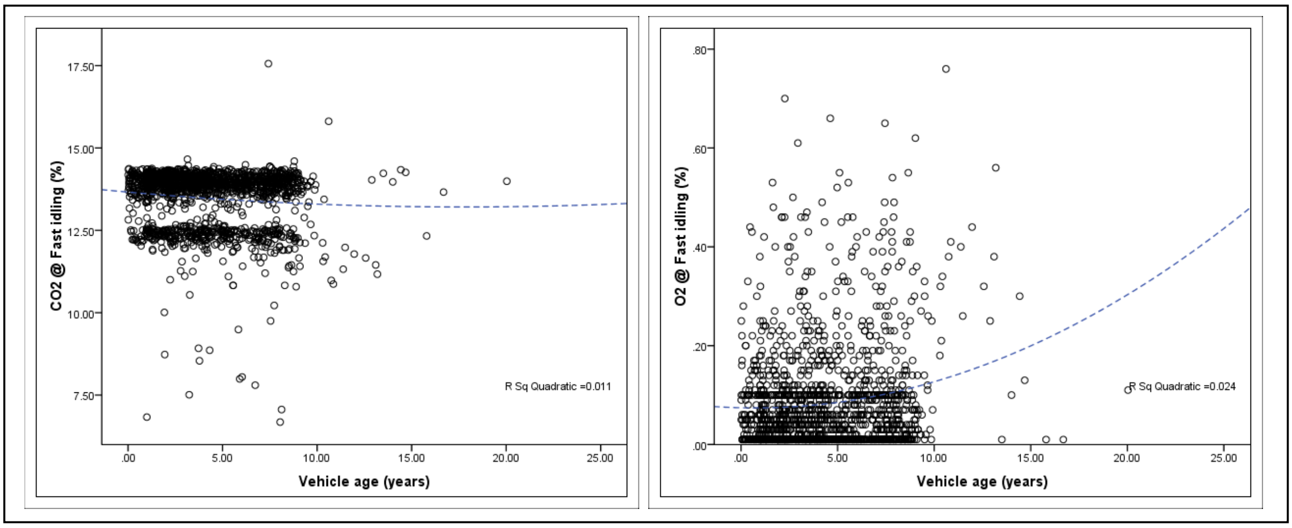


Fig. 4.3 Vehicle age vs. CO_2 and O_2 emissions (at fast idling)

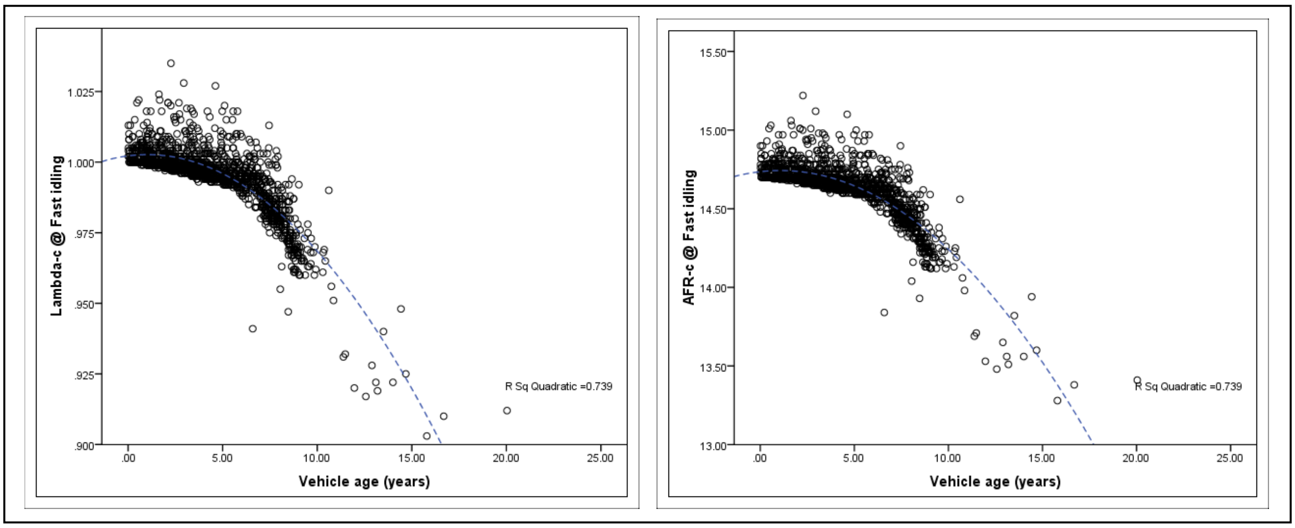


Fig. 4.4 Vehicle age vs. λ and AFR (at fast idling)

Table 4.3: Emission equations with respect to vehicle age (whole dataset)

Parameter	Equation	R^2
CO @ Idling	$y = 0.0174x^2 - 0.0772x + 0.0615$	0.881
CO @ Fast idling	$y = 0.0087x^2 - 0.063x + 0.0908$	0.603
HC @ Idling	$y = -0.4401x^2 + 20.663x + 18.968$	0.729
HC @ Fast idling	$y = -0.1592x^2 + 7.739x + 20.058$	0.561
CO_2 @ Fast idling	$y = 0.0014x^2 - 0.0509x + 13.661$	0.011
O_2 @ Fast idling	$y = 0.0006x^2 - 0.0009x + 0.0743$	0.024
λ @ Fast idling	$y = -0.0004x^2 + 0.0009x + 1.0022$	0.739
AFR @ Fast idling	$y = -0.0063x^2 + 0.0134x + 14.736$	0.738

The field-measured tailpipe emission parameters with respect to vehicle age were also plotted for the top 3 makes and top 16 models of petrol-driven passenger cars, based on their representativeness in the sample size. This additional analysis aimed at better data resolution and variability amongst makes and models apart from whole data. The data was analyzed for idle and fast idle test modes and the results are shown in Figures 4.5, 4.6, 4.7 and 4.8 for the top 3 makes and in Figures 4.9, 4.10, 4.11 and 4.12 for top 16 models, respectively.

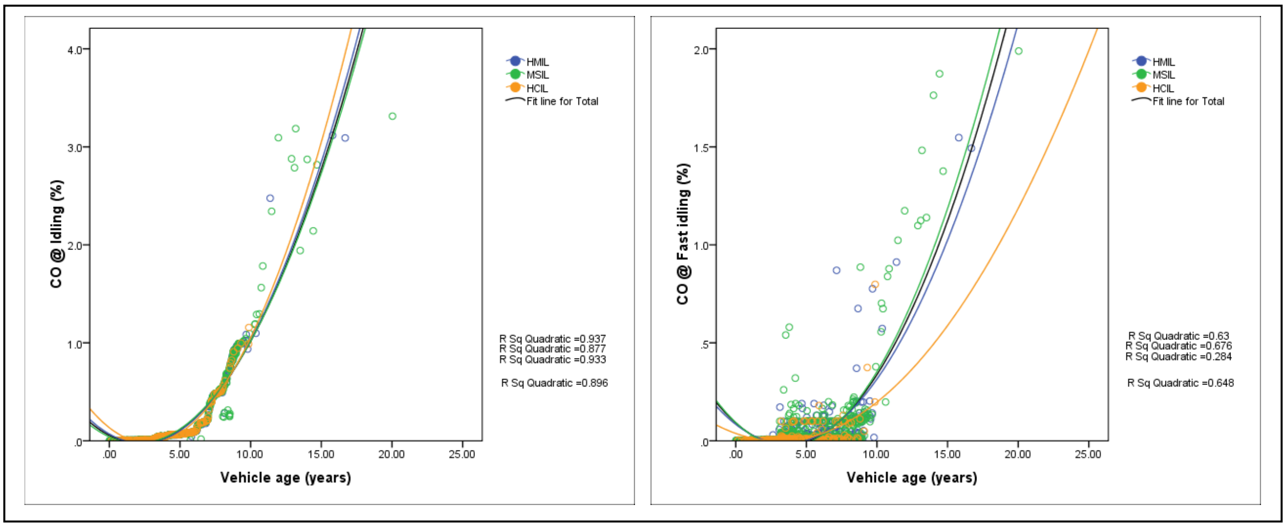


Fig. 4.5 Vehicle age vs. CO emission for top 3 makes (at idling and fast idling)

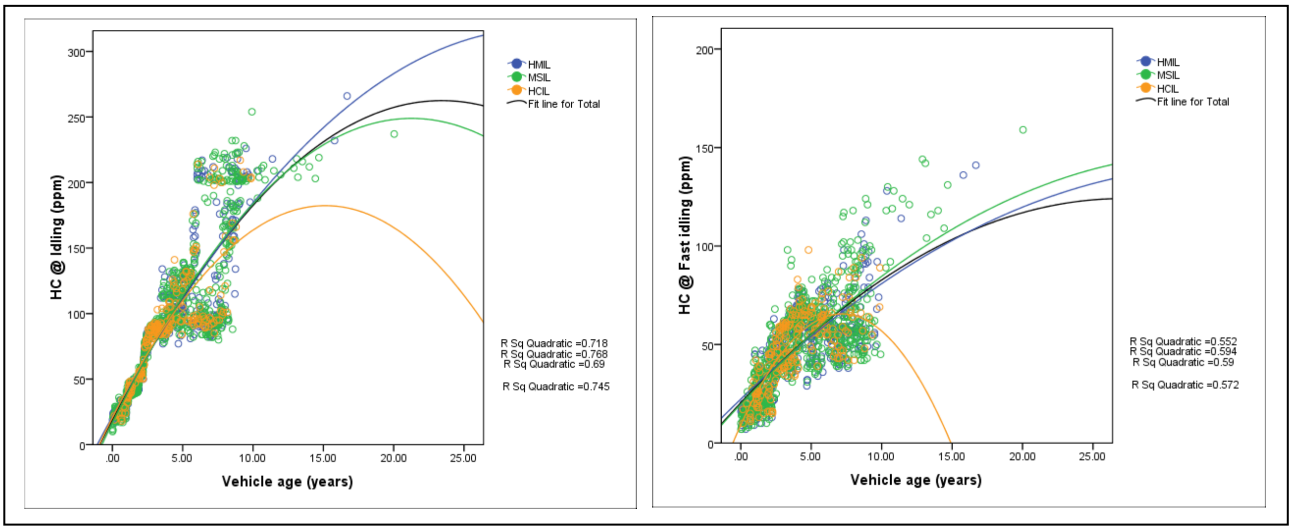


Fig. 4.6 Vehicle age vs. HC emission for top 3 makes (at idling and fast idling)

It is again observed that the dependence of emission levels on vehicle age is polynomial or quadric in nature. The resultant emission equations and R^2 values obtained for the best-fit quadratic trendlines in the case of top 3 makes are presented in Table 4.4 and the same for top 16 models are presented in four different tables due to larger data (Tables 4.5, 4.6, 4.7 and 4.8 respectively).

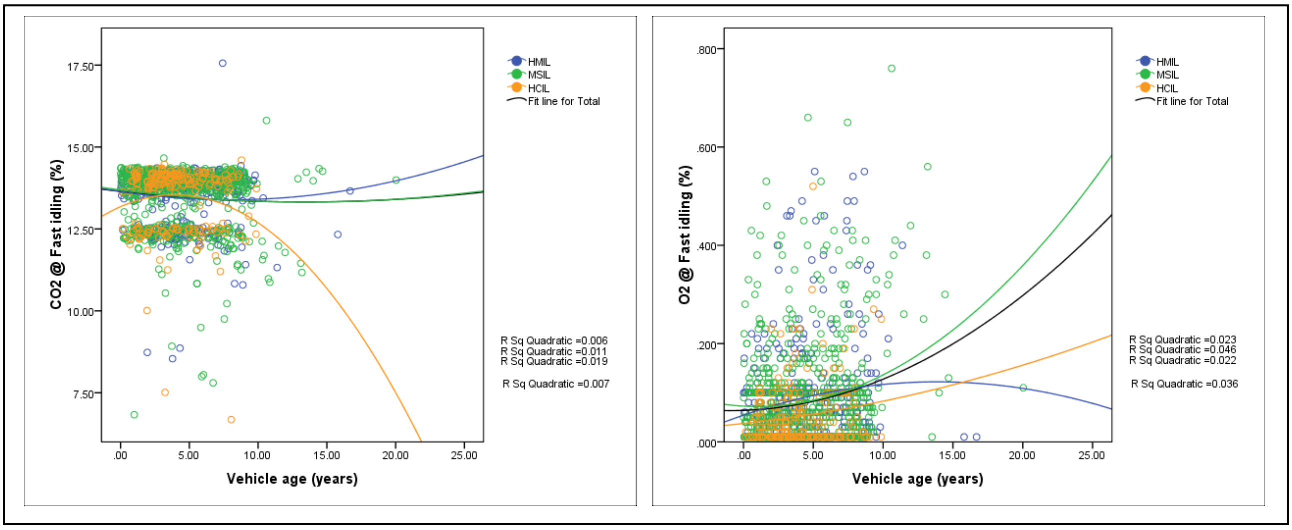


Fig. 4.7 Vehicle age vs. CO₂ and O₂ emission for top 3 makes (at fast idling)

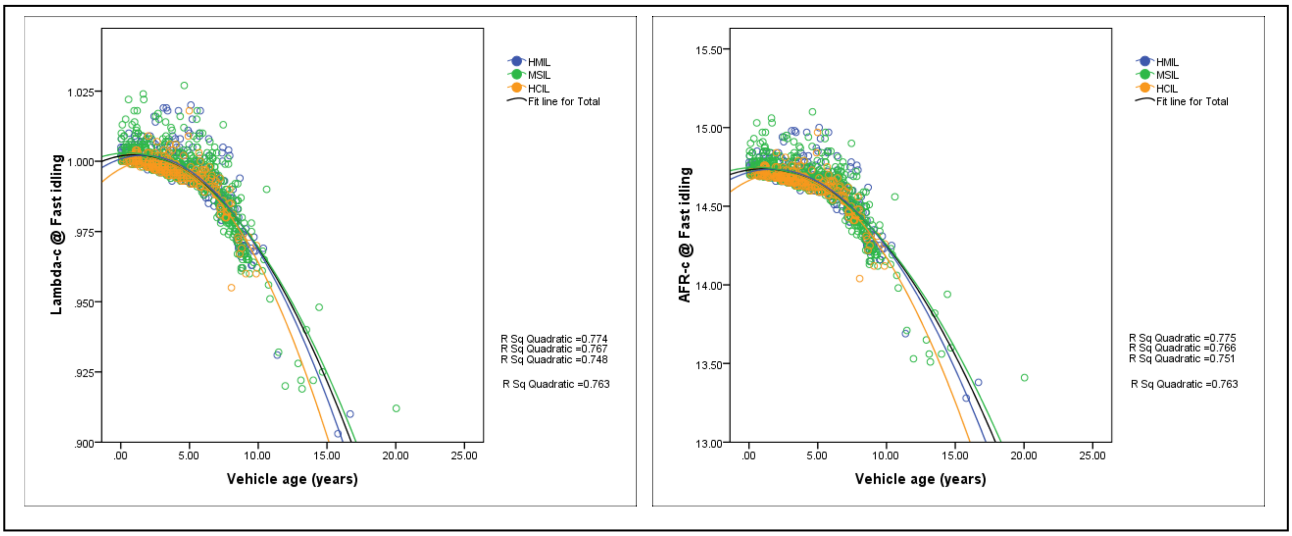


Fig. 4.8 Vehicle age vs. λ and AFR for top 3 makes (at fast idling)

Table 4.4: Emission equations with respect to vehicle age (top 3 makes)

Parameter	MSIL		HMIL		HCIL	
	Equation	R^2	Equation	R^2	Equation	R^2
CO @ Idling	$y = 0.0163x^2 - 0.0655x + 0.0404$	0.877	$y = 0.0178x^2 - 0.0821x + 0.0696$	0.937	$y = 0.0205x^2 - 0.1127x + 0.1339$	0.933
CO @ Fast idling	$y = 0.0094x^2 - 0.0678x + 0.0935$	0.676	$y = 0.0079x^2 - 0.0559x + 0.0838$	0.631	$y = 0.0041x^2 - 0.0254x + 0.0377$	0.284
HC @ Idling	$y = -0.5139x^2 + 21.854x + 16.574$	0.768	$y = -0.322x^2 + 19.525x + 21.428$	0.718	$y = -0.7055x^2 + 21.364x + 20.595$	0.692
HC @ Fast idling	$y = -0.1144x^2 +$	0.594	$y = -0.0991x^2 +$	0.552	$y = -1.0946x^2 +$	0.592

	$7.6276x + 19.781$		$6.8566x + 22.266$		$15.711x + 9.1707$	
CO_2 @ Fast idling	$y = 0.002x^2 - 0.0549x + 13.69$	0.011	$y = 0.0046x^2 - 0.066x + 13.637$	0.006	$y = -0.0234x^2 + 0.1849x + 13.179$	0.019
O_2 @ Fast idling	$y = 0.0008x^2 - 0.0016x + 0.0728$	0.046	$y = -0.0004x^2 + 0.0098x + 0.0545$	0.023	$y = 0.0001x^2 + 0.0032x + 0.0375$	0.022
λ @ Fast idling	$y = -0.0004x^2 + 0.0004x + 1.0029$	0.767	$y = -0.0005x^2 + 0.0016x + 1.0009$	0.774	$y = -0.0006x^2 + 0.0027x + 0.9974$	0.748
AFR @ Fast idling	$y = -0.0055x^2 + 0.0065x + 14.745$	0.766	$y = -0.0072x^2 + 0.0238x + 14.716$	0.775	$y = -0.009x^2 + 0.0405x + 14.664$	0.751

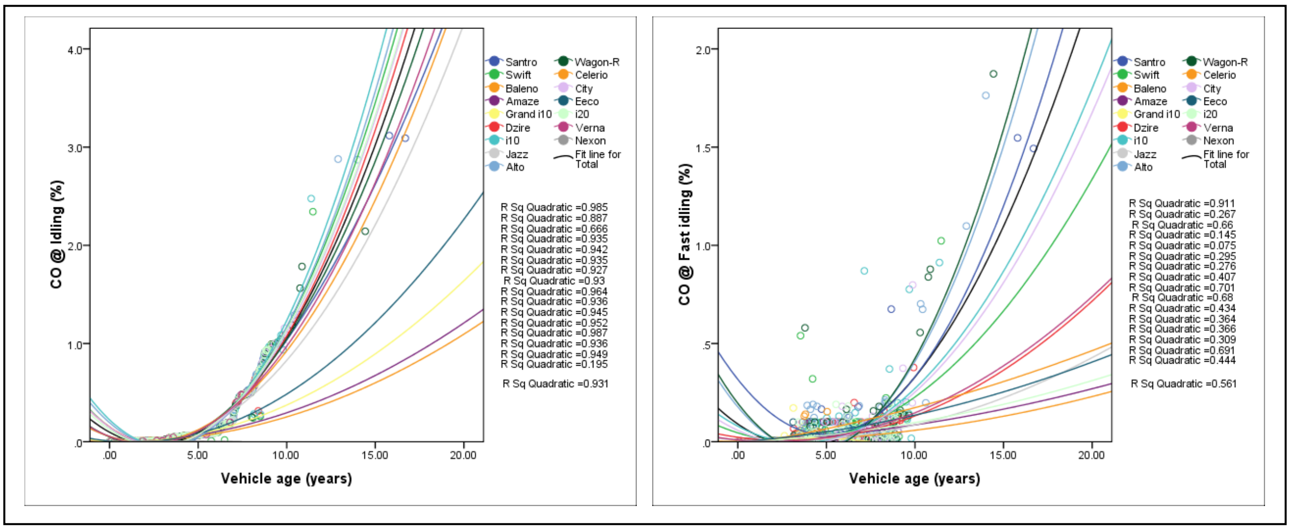


Fig. 4.9 Vehicle age vs. CO emission for top 16 models (at idling and fast idling)

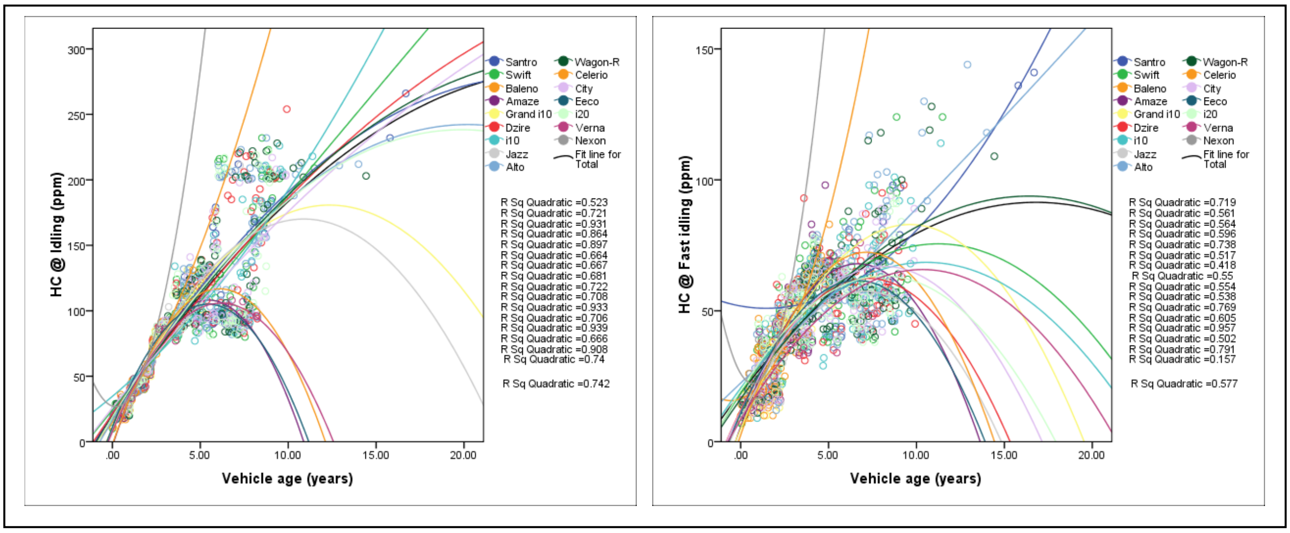


Fig. 4.10 Vehicle age vs. HC emission for top 16 models (at idling and fast idling)

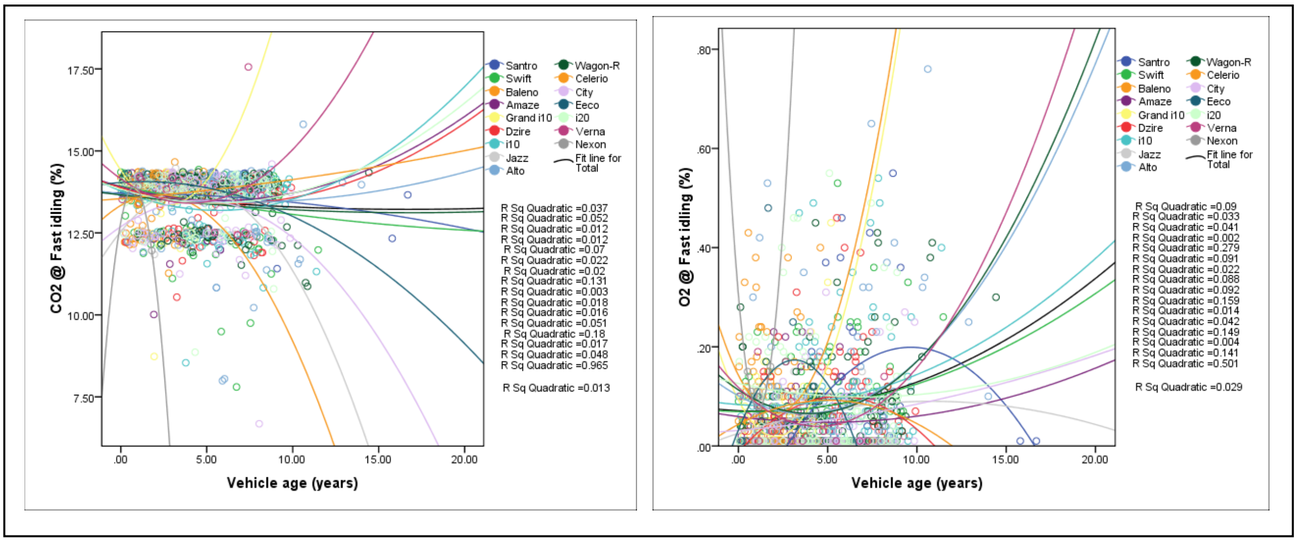


Fig. 4.11 Vehicle age vs. CO_2 and O_2 emission for top 16 models (at fast idling)

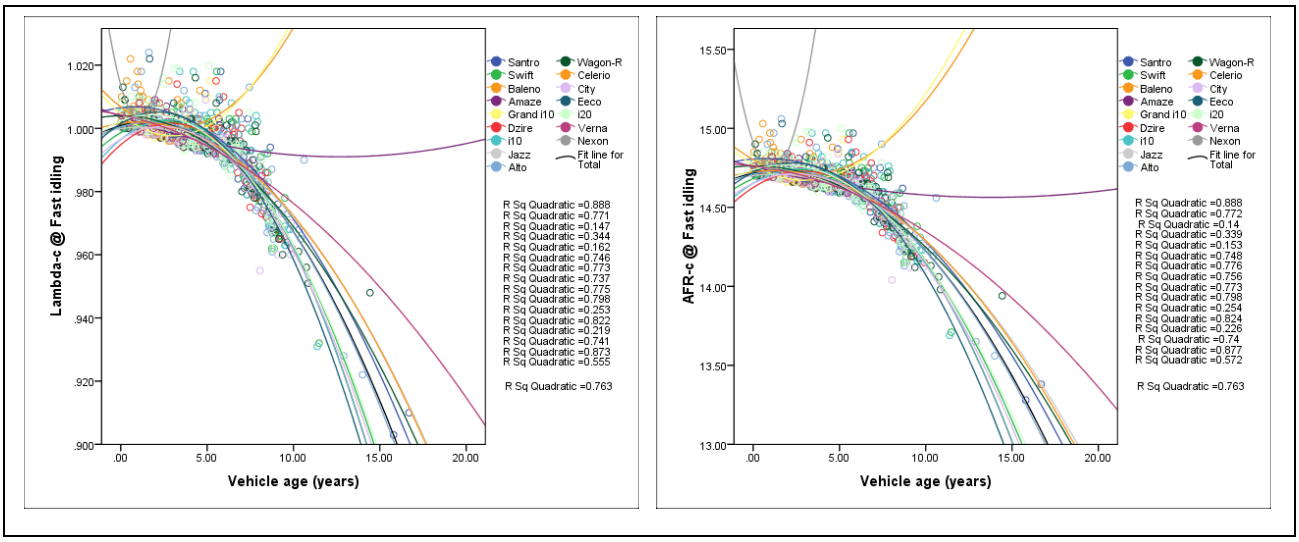


Fig. 4.12 Vehicle age vs. λ and AFR for top 16 models (at fast idling)

Table 4.5: Emission equations with respect to vehicle age (top 16 models – part 1/4)

Parameter	**Santro**		**Swift**		**Baleno**		**Amaze**	
	Equation	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**
CO @ Idling	$y = 0.0119x^2 + 0.0188x - 0.3457$	0.985	$y = 0.0237x^2 - 0.135x + 0.1465$	0.887	$y = 0.003x^2 - 0.005x + 0.005$	0.667	$y = 0.0031x^2 - 0.0012x - 0.002$	0.935
HC @ Idling	$y = -0.4433x^2 + 21.374x + 21.459$	0.523	$y = -0.0221x^2 + 16.613x + 24.222$	0.721	$y = 1.6945x^2 + 18.18x + 15.019$	0.931	$y = -3.7088x^2 + 40.664x - 3.2962$	0.864
CO_2 @ Fast idling	$y = -0.0307x^2 + 0.3398x + 12.757$	0.037	$y = 0.0019x^2 - 0.1047x + 13.921$	0.052	$y = -0.0715x^2 + 0.3082x + 13.341$	0.012	$y = 0.0128x^2 - 0.1467x + 13.91$	0.012
O_2 @ Fast idling	$y = -0.0041x^2 + 0.0798x - 0.1864$	0.091	$y = 0.0006x^2 - 0.0008x + 0.0694$	0.033	$y = 0.017x^2 - 0.072x + 0.1427$	0.041	$y = 0.0005x^2 - 0.0046x + 0.0593$	0.002
λ @ Fast idling	$y = -0.0004x^2 + 0.0007x + 1.0065$	0.088	$y = -0.0007x^2 + 0.0032x + 0.9986$	0.771	$y = 0.0007x^2 - 0.0042x + 1.0068$	0.147	$y = 0.00008x^2 - 0.00200x + 1.00370$	0.344
AFR @ Fast idling	$y = -0.0061x^2 + 0.0087x + 14.806$	0.888	$y = -0.01x^2 + 0.0474x + 14.682$	0.772	$y = 0.0098x^2 - 0.0614x + 14.802$	0.142	$y = 0.001x^2 - 0.028x + 14.757$	0.339

Table 4.6: Emission equations with respect to vehicle age (top 16 models – part 2/4)

Parameter	**Grand i10**		**Dzire**		**i10**		**Jazz**	
	Equation	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**
CO @ Idling	$y = 0.0045x^2 - 0.0078x + 0.0047$	0.942	$y = 0.0218x^2 - 0.1254x + 0.1493$	0.935	$y = 0.0272x^2 - 0.1709x + 0.2223$	0.927	$y = 0.0133x^2 - 0.055x + 0.054$	0.931
HC @ Idling	$y = -1.1281x^2 + 27.743x + 9.6773$	0.897	$y = -0.2714x^2 + 19.195x + 21.179$	0.664	$y = 0.4444x^2 + 11.32x + 34.653$	0.667	$y = -1.3542x^2 + 29.582x + 8.7814$	0.681

CO_2 @ Fast idling	$y = 0.1434x^2 - 0.7777x + 14.409$	0.07	$y = 0.0129x^2 - 0.1588x + 13.876$	0.022	$y = 0.0184x^2 - 0.2087x + 13.777$	0.021	$y = -0.0759x^2 + 0.6385x + 12.545$	0.131
O_2 @ Fast idling	$y = 0.017x^2 - 0.071x + 0.0933$	0.279	$y = -0.0035x^2 + 0.0397x - 0.0122$	0.091	$y = 0.0009x^2 - 0.0026x + 0.0836$	0.022	$y = -0.0005x^2 + 0.0119x + 0.0258$	0.088
λ @ Fast idling	$y = 0.0008x^2 - 0.0046x + 1.0046$	0.162	$y = -0.0008x^2 + 0.0046x + 0.9948$	0.746	$y = -0.0008x^2 + 0.0044x + 0.9965$	0.773	$y = -0.0004x^2 + 0.0008x + 0.9999$	0.737
AFR @ Fast idling	$y = 0.0111x^2 - 0.0658x + 14.769$	0.153	$y = -0.0118x^2 + 0.0697x + 14.625$	0.748	$y = -0.0116x^2 + 0.0651x + 14.653$	0.775	$y = -0.0056x^2 + 0.014x + 14.701$	0.757

Table 4.7: Emission equations with respect to vehicle age (top 16 models – part 3/4)

Parameter	**Alto**		**Wagon-R**		**Celerio**		**City**	
	Equation	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**
CO @ Idling	$y = 0.0254x^2 - 0.1563x + 0.1933$	0.964	$y = 0.0176x^2 - 0.076x + 0.049$	0.936	$y = 0.0147x^2 - 0.0594x + 0.0531$	0.945	$y = 0.0225x^2 - 0.1283x + 0.1462$	0.952
HC @ Idling	$y = -0.5536x^2 + 22.363x + 16.246$	0.722	$y = -0.3983x^2 + 20.933x + 18.966$	0.708	$y = -3.2186x^2 + 39.165x - 2.3496$	0.933	$y = -0.1975x^2 + 16.955x + 25.906$	0.706
CO_2 @ Fast idling	$y = 0.0053x^2 - 0.0727x + 13.679$	0.003	$y = 0.0019x^2 - 0.064x + 13.658$	0.018	$y = 0.0015x^2 + 0.043x + 13.546$	0.016	$y = -0.0386x^2 + 0.3524x + 12.69$	0.051
O_2 @ Fast idling	$y = 0.0027x^2 - 0.0195x + 0.1013$	0.092	$y = 0.0029x^2 - 0.0237x + 0.1132$	0.159	$y = -0.0019x^2 + 0.0194x + 0.0434$	0.014	$y = 0.0002x^2 + 0.003x + 0.0316$	0.042
λ @ Fast idling	$y = -0.0005x^2 + 0.0018x + 1.0005$	0.775	$y = -0.00035x^2 + 0.00001x + 1.00396$	0.798	$y = -0.0004x^2 + 0.0008x + 1.0016$	0.253	$y = -0.0007x^2 + 0.0033x + 0.9966$	0.822
AFR @ Fast idling	$y = -0.0075x^2 + 0.0267x + 14.71$	0.773	$y = -0.0052x^2 + 0.0007x + 14.762$	0.798	$y = -0.0057x^2 + 0.0138x + 14.724$	0.254	$y = -0.0102x^2 + 0.0499x + 14.652$	0.824

Table 4.8: Emission equations with respect to vehicle age (top 16 models – part 4/4)

Parameter	**Eeco**		**i20**		**Verna**		**Nexon**	
	Equation	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**
CO @ Idling	$y = 0.0065x^2 - 0.0171x + 0.0067$	0.987	$y = 0.0223x^2 - 0.1212x + 0.1219$	0.936	$y = 0.0161x^2 - 0.069x + 0.0529$	0.949	$y = -0.0004x^2 + 0.0031x + 0.0008$	0.195
HC @ Idling	$y = -3.1937x^2 + 34.659x + 10.988$	0.939	$y = -0.5575x^2 + 22.113x + 18.818$	0.667	$y = -2.5822x^2 + 31.853x + 7.5824$	0.908	$y = 11.545x^2 - 5.1765x + 27.575$	0.742
CO_2 @ Fast idling	$y = -0.0143x^2 + 0.0395x + 14.036$	0.181	$y = 0.0144x^2 - 0.1561x + 13.831$	0.017	$y = 0.046x^2 - 0.3702x + 14.15$	0.048	$y = -1.8473x^2 + 2.8353x + 12.82$	0.965
O_2 @ Fast idling	$y = -0.0142x^2 + 0.0897x + 0.0321$	0.149	$y = 0.0005x^2 - 0.0077x + 0.1261$	0.004	$y = 0.0039x^2 - 0.035x + 0.1181$	0.141	$y = 0.189x^2 - 0.4181x + 0.3059$	0.501
λ @ Fast idling	$y = -0.0008x^2 + 0.0033x + 1.0015$	0.219	$y = -0.0006x^2 + 0.0022x + 1.0024$	0.741	$y = -0.0002x^2 - 0.0011x + 1.0043$	0.873	$y = 0.0089x^2 - 0.0197x + 1.0136$	0.555
AFR @ Fast idling	$y = -0.0118x^2 + 0.0535x + 14.721$	0.226	$y = -0.0091x^2 + 0.0327x + 14.738$	0.741	$y = -0.0028x^2 - 0.0132x + 14.762$	0.877	$y = 0.1404x^2 - 0.3074x + 14.911$	0.572

A glance at the emission equations having vehicle age as an independent variable reveals that, the ageing of cars has a direct influence on emission characteristics. This may lead to non-compliance of the vehicles towards concurrent emission norms thereby necessitating a quick (in the form of engine tuning or replacement of the catalytic converter etc.) or long-haul inspection (in the form of maintenance of the whole vehicle). Although a significant data scattering may be observed in fast idling conditions for both CO and HC (Fig. 4.1 and 4.2, 4.4 and Table 4.2) resulting into a relatively poorer correlation value ($R^2 = 0.603$ and 0.561 respectively). This might be attributable to the fact that high idle condition (high engine RPM) is difficult to be idealized and in many cases, is accompanied by abrupt variations in engine speed and therefore, unsteadied concentrations encountered in the corresponding readings.

The emission equations further computed for the top 3 makes are generally in line with those for the whole data set except for HCIL make which show a poor or no correlation while comparing vehicle age vs. Fast idling CO ($R^2 = 0.284$). Upon further examining the top 16 models for their emission equations, a few models showed a poor correlation for age vs. CO @ Fast idling, for e.g., Swift, Amaze, Grand i10, Dzire, i10, i20 and Eeco ($R^2 < 0.4$). Only one model, Nexon, reported no correlation between age and HC @ Fast idling ($R^2 < 0.2$). While the reason behind such poor correlation can be explained by the difficulty in attaining and maintaining the high idle conditions, the one instance of no correlation of Nexon can be attributed to its sample size (n = 6, 0.38%) and most possibly, a good no. of Nexon cars in the sample may have bettered the correlation (Fig. 4.10, Tables 4.4 – 4.8).

The study further indicated that CO_2 and O_2 exhaust concentrations do not seem to be affected by the vehicle age for fast idling conditions for all the analysis cases, i.e., entire data set, top 3 makes and top 16 models. (Figs. 4.3, 4.7 and 4.11; Tables 4.2 – 4.8) whereas λ and AFR @ Fast idling were found to be fairly correlated with vehicle age (Figs. 4.4, 4.8 and 4.12; Tables 4.1 – 4.6). A comparison of emission equations along with correlation coefficients for different dataset conditions is presented in Table 4.9.

Table 4.9: Emission equations for different datasets with respect to vehicle age

Data set	**Entire (n=1580)**		**Top 3 makes (n=1321)**		**Top 16 models (n=1115)**	
Parameters	**Equation**	**R^2**	**Equation**	**Parameters**	**Equation**	**R^2**
CO @ Idling	$y = 0.0174x^2 - 0.0772x + 0.0615$	0.881	$y = 0.017x^2 - 0.0737x + 0.0557$	0.937	$y = 0.0196x^2 - 0.099x + 0.0966$	0.931
CO @ Fast idling	$y = 0.0087x^2 - 0.063x + 0.0908$	0.603	$y = 0.0088x^2 - 0.0635x + 0.0911$	0.648	$y = 0.0086x^2 - 0.0624x + 0.09$	0.561
HC @ Idling	$y = -0.4401x^2 + 20.663x + 18.968$	0.729	$y = -0.4447x^2 + 20.818x + 18.82$	0.745	$y = -0.386x^2 + 20.237x + 19.756$	0.742
HC @ Fast idling	$y = -0.1592x^2 + 7.739x + 20.058$	0.561	$y = -0.1407x^2 + 7.637x + 20.441$	0.572	$y = -0.2586x^2 + 8.6774x + 18.617$	0.577
CO_2 @ Fast idling	$y = 0.0014x^2 - 0.0509x + 13.661$	0.011	$y = 0.0018x^2 - 0.048x + 13.644$	0.007	$y = 0.0017x^2 - 0.056x + 13.684$	0.013
O_2 @ Fast idling	$y = 0.0006x^2 - 0.0009x + 0.0743$	0.024	$y = 0.0005x^2 + 0.001x + 0.0641$	0.036	$y = 0.0008x^2 - 0.0018x + 0.0712$	0.029
λ @ Fast idling	$y = -0.0004x^2 + 0.0009x + 1.0022$	0.739	$y = -0.0004x^2 + 0.0008x + 1.0019$	0.763	$y = -0.0005x^2 + 0.0015x + 1.0009$	0.763
AFR @ Fast idling	$y = -0.0063x^2 + 0.0134x + 14.736$	0.738	$y = -0.0061x^2 + 0.0129x + 14.731$	0.762	$y = -0.0073x^2 + 0.0233x + 14.716$	0.763

An overview of the plots also indicates the comparative standing of trendlines for the top 3 makes and top 16 models basis their representation in the entire data set. Assuming the trendlines to be the guiding factor, the relative standing of different makes and models in terms of their idle CO and HC emissions (in both testing modes) due to ageing effects in descending order is presented in Tables 4.10 and 4.11.

Table 4.10: Relative standing of different makes in descending order in terms of their CO and HC emissions due to age factor

S. No.	Ageing effect on CO emission		Ageing effect on HC emission	
	Idling	**Fast idling**	**Idling**	**Fast idling**
1.	HCIL	MSIL	HMIL	MSIL
2.	HMIL	HMIL	MSIL	HMIL
3.	MSIL	HCIL	HCIL	HCIL

Table 4.11: Relative standing of different models in descending order in terms of their CO and HC emissions due to age factor

S. No.	Ageing effect on CO emission			Ageing effect on HC emission		
	Idling	**Fast idling**	**Change in standing**	**Idling**	**Fast idling**	**Change in standing**
1.	i10	Wagon-R	↑	Nexon	Nexon	↔
2.	Alto	Alto	↔	Baleno	Baleno	↔
3.	Swift	Santro	↑	i10	Santro	↑
4.	i20	i10	↓	Swift	Alto	↑
5.	Nexon	City	↑	Dzire	Wagon-R	↑
6.	City	Swift	↓	City	Swift	↓
7.	Dzire	Verna	↑	Wagon-R	i10	↓
8.	Wagon-R	Dzire	↓	Santro	Verna	↑
9.	Verna	Grand i10	↑	Alto	Grand i10	↑
10.	Santro	Baleno	↑	i20	i20	↔
11.	Baleno	Nexon	↓	Grand i10	City	↓
12.	Jazz	Eeco	↑	Jazz	Dzire	↓
13.	Eeco	Jazz	↓	Celerio	Jazz	↓
14.	Grand i10	i20	↓	Verna	Celerio	↓
15.	Amaze	Amaze	↔	Eeco	Eeco	↔
16.	Celerio	Celerio	↔	Amaze	Amaze	↔

↓ *= standing down from earlier position* ↑ *= standing up from earlier position* ↔ *= no change in earlier position*

4.1.1.2 Vehicle mileage

Figures 4.13 and 4.14 present the plots drawn to understand as to how vehicle mileage is related to CO and HC emission in both idle and fast idle testing modes for the entire dataset. As can be seen, a 2nd order polynomial curve best describes the emission characteristics for both pollutants, even if the scatter in data is vivid. The resultant R^2 values were a good indication of how the entire dataset behaved in the scatterplots giving a conclusive picture.

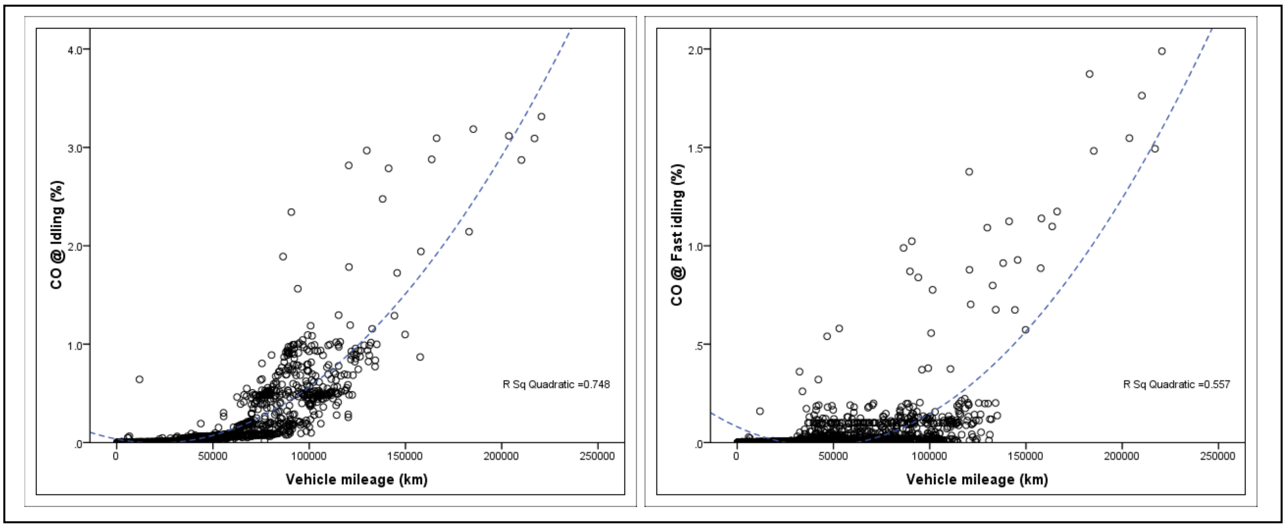


Fig. 4.13 Vehicle mileage vs. CO emission (at idling and fast idling)

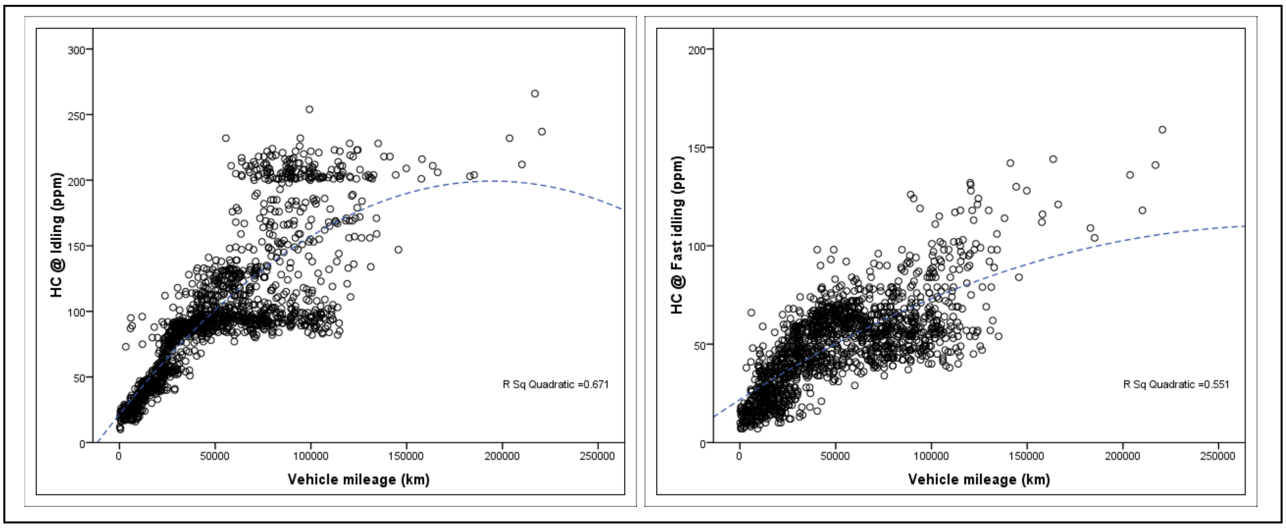


Fig. 4.14 Vehicle mileage vs. HC emission (at idling and fast idling)

The graphical analysis was also applied to investigate the effect of vehicle mileage on other emission / emission-related parameters, i.e., CO_2, O_2, λ and AFR. As per the study methodology and certification testing protocol, the CO and HC concentrations were recorded for both idle and fast idle conditions whereas only fast idle testing was conducted for the other four parameters. CO_2 and O_2 emissions along with λ and AFR for the entire data range are shown in Figures 4.15 and 4.16 respectively. It was found that vehicle mileage is significantly and negatively related to λ and AFR implying that vehicles with more accumulated mileage show reduced values for both λ and AFR.

On the other hand, no correlation could be established between the other two parameters, i.e., CO_2 and O_2 emissions in respect of vehicle mileage with R^2 values to be too low. The emission equations along with corresponding R^2 values computed using 2nd order polynomial curve presenting the likelihood of correlation amongst all eight parameters with respect to vehicle mileage for idle and fast idle test methods are given in Table 4.12.

Table 4.12: Emission equations with respect to vehicle mileage (whole dataset)

Parameter	**Equation**	**R^2**
CO @ Idling	$y = 0.0000000001x^2 - 0.0000037836x + 0.0346$	0.748
CO @ Fast idling	$y = 0.0000000001x^2 - 0.0000044730x + 0.0801$	0.557
HC @ Idling	$y = -0.0000000047x^2 + 0.0018247565x + 21.6145$	0.671
HC @ Fast idling	$y = -0.0000000011x^2 + 0.0006223787x + 21.8187$	0.551
CO_2 @ Fast idling	$y = 0.00000000001x^2 - 0.00000366929x + 13.6214$	0.007
O_2 @ Fast idling	$y = 0.000000000004x^2 - 0.000000045484x + 0.0741$	0.026
λ @ Fast idling	$y = -0.000000000002x^2 - 0.000000004131x + 1.0027$	0.622
AFR @ Fast idling	$y = -0.00000000003x^2 - 0.00000000697x + 14.7436$	0.621

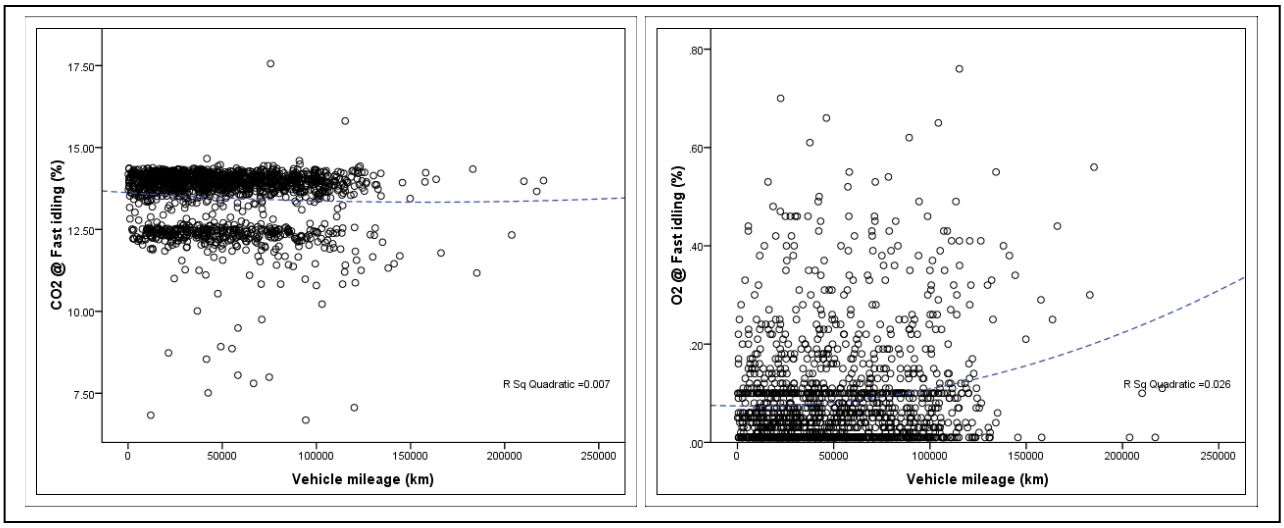


Fig. 4.15 Vehicle mileage vs. CO_2 and O_2 emissions (at fast idling)

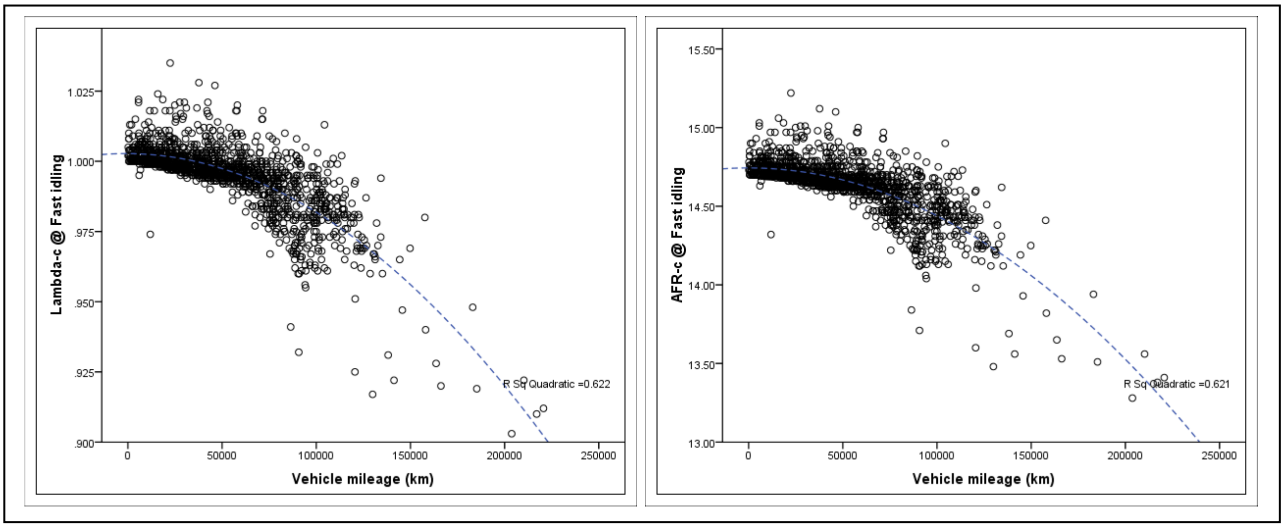


Fig. 4.16 Vehicle mileage vs. λ and AFR (at fast idling)

The measured concentration data points for tailpipe emission parameters vis-a-vis vehicle mileage were also plotted for the top 3 makes and top 16 models of passenger cars under investigation. The data using SPSS and MS-Excel was analyzed for idle and fast idle test modes and the results are presented in Figures 4.17, 4.18, 4.19 and 4.20 for the top 3 makes and in Figures 4.21, 4.22, 4.23 and 4.24 respectively. It is again observed that the dependence of emission levels or parameters on vehicle mileage is quadric in nature giving the best-fit for trendlines. The resultant emission equations and R^2 values obtained from such quadratic trendlines in the case of top 3 makes are presented in Table 4.13 and the same for and top 16 models are presented in four different tables (Tables 4.14, 4.15, 4.16 and 4.17 respectively).

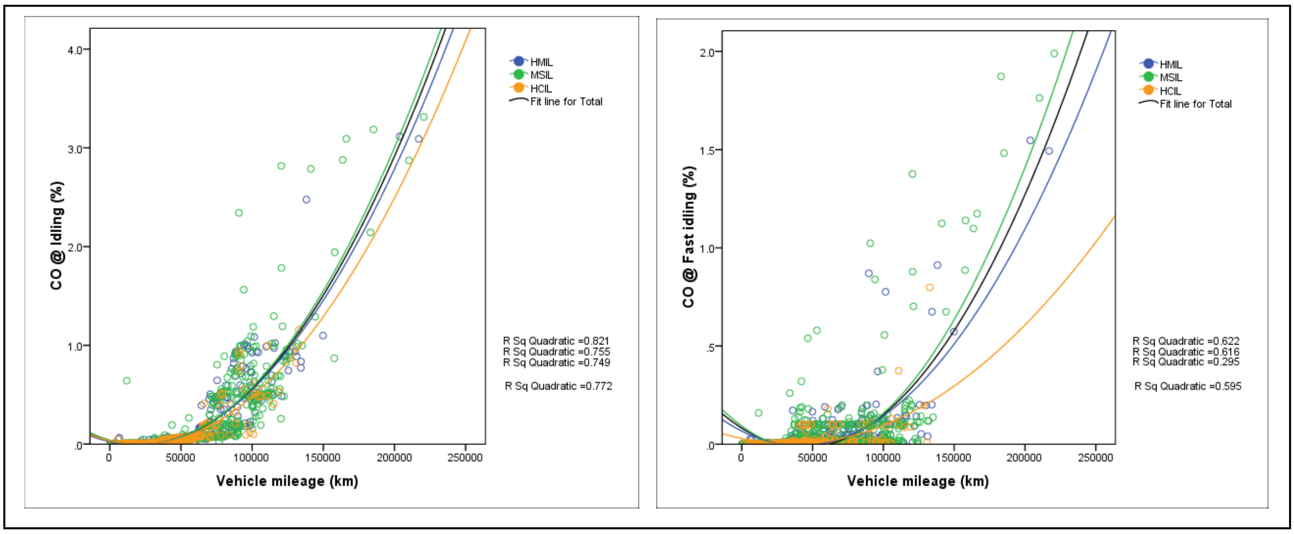


Fig. 4.17 Vehicle mileage vs. CO emission for top 3 makes (at idling and fast idling)

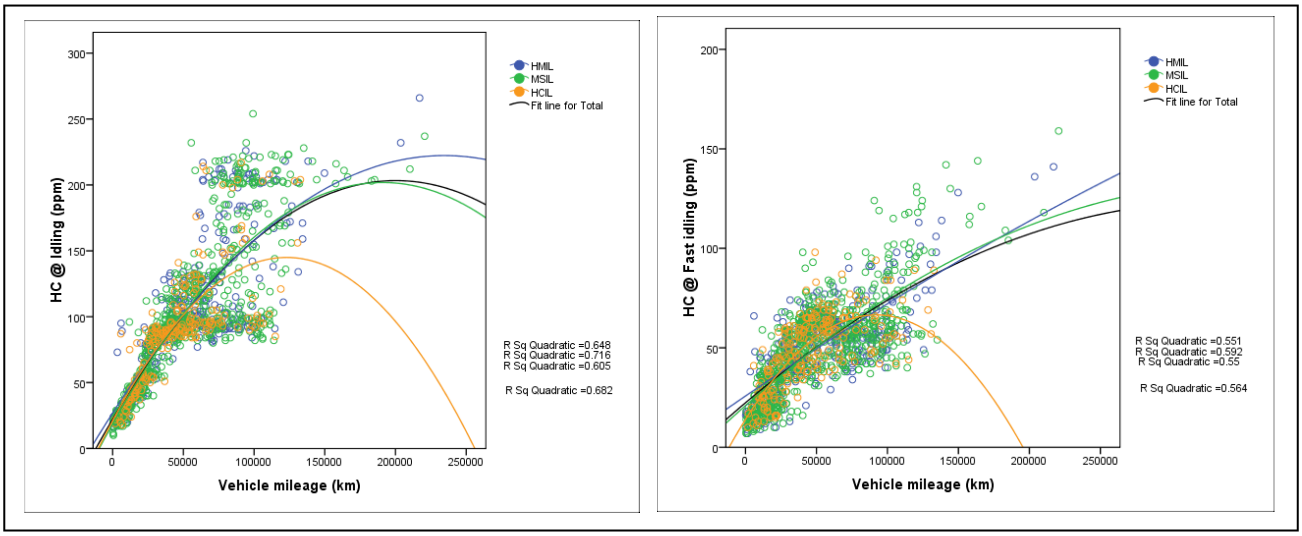


Fig. 4.18 Vehicle mileage vs. HC emission for top 3 makes (at idling and fast idling)

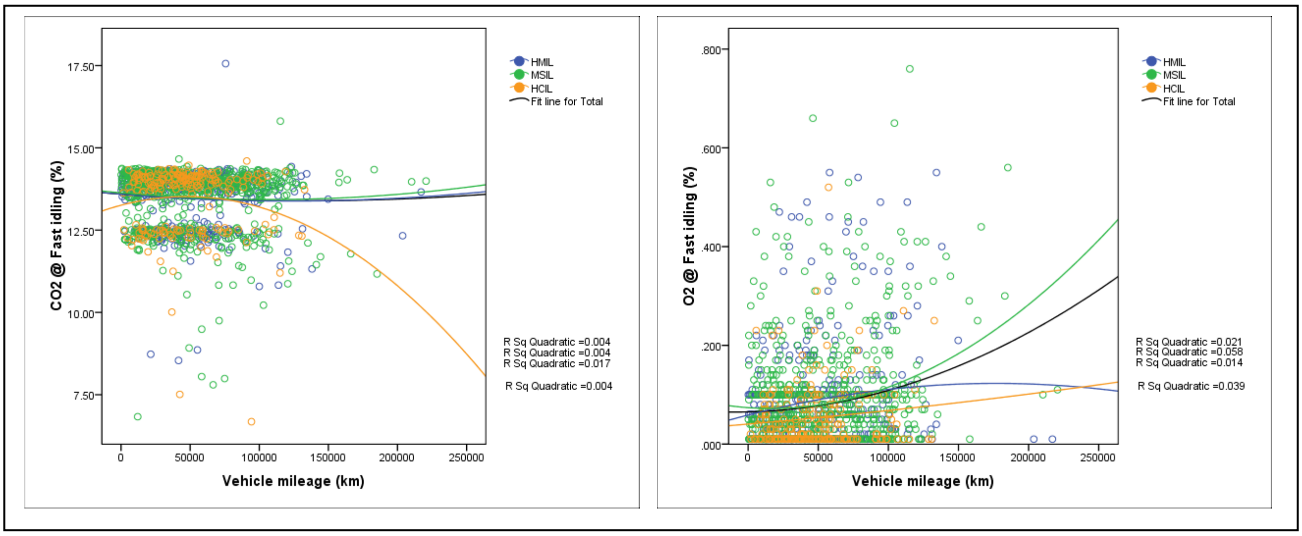


Fig. 4.19 Vehicle mileage vs. CO_2 and O_2 emission for top 3 makes (at fast idling)

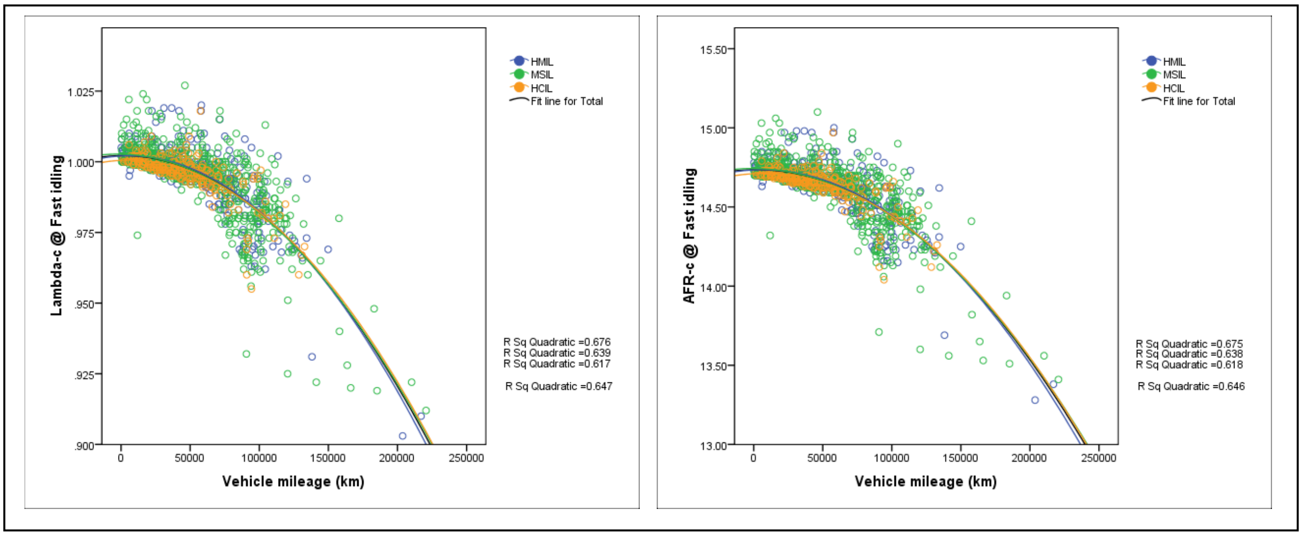


Fig. 4.20 Vehicle mileage vs. λ and AFR for top 3 makes (at fast idling)

Table 4.13: Emission equations with respect to vehicle mileage (top 3 makes)

Parameter	MSIL		HMIL		HCIL	
	Equation	R^2	Equation	R^2	Equation	R^2
CO @ Idling	$y = 0.0000000001x^2 - 0.0000041163x + 0.0393$	0.755	$y = 0.0000000001x^2 - 0.0000032311x + 0.0233$	0.821	$y = 0.0000000001x^2 - 0.0000033536x + 0.0338$	0.749
CO @ Fast idling	$y = 0.0000000001x^2 - 0.0000052871x + 0.0923$	0.616	$y = 0.00000000004x^2 - 0.00000361277x + 0.0668$	0.622	$y = 0.00000000002x^2 - 0.00000154364x + 0.0285$	0.295
HC @ Idling	$y = -0.000000005x^2 + 0.001918944x + 18.7679$	0.716	$y = -0.000000004x^2 + 0.001665741x + 26.9806$	0.648	$y = -0.000000008x^2 + 0.002013920x + 21.1361$	0.605
HC @ Fast idling	$y = -0.000000006x^2 + 0.001141895x + 14.0273$	0.592	$y = -0.0000000002x^2 + 0.0004876134x + 25.7874$	0.551	$y = -0.0000000009x^2 + 0.0006295487x + 20.9631$	0.551
CO_2 @ Fast idling	$y = 0.00000000002x^2 - 0.00000385452x + 13.6335$	0.004	$y = 0.00000000001x^2 - 0.00000345688x + 13.5927$	0.004	$y = -0.0000000001x^2 + 0.0000111342x + 13.2564$	0.017
O_2 @ Fast idling	$y = 0.000000000006x^2 - 0.000000212153x + 0.0737$	0.058	$y = -0.000000000002x^2 + 0.000000725923x + 0.0587$	0.021	$y = 0.0000000000003x^2 + 0.0000002462571x + 0.0405$	0.014
λ @ Fast idling	$y = -0.000000000002x^2 - 0.000000009572x + 1.0027$	0.639	$y = -0.000000000002x^2 + 0.000000025717x + 1.0021$	0.676	$y = -0.000000000002x^2 + 0.000000026046x + 1.0005$	0.617
AFR @ Fast idling	$y = -0.00000000003x^2 - 0.00000008273x + 14.7430$	0.638	$y = -0.00000000003x^2 + 0.00000040785x + 14.7341$	0.675	$y = -0.00000000003x^2 + 0.00000047583x + 14.7105$	0.618

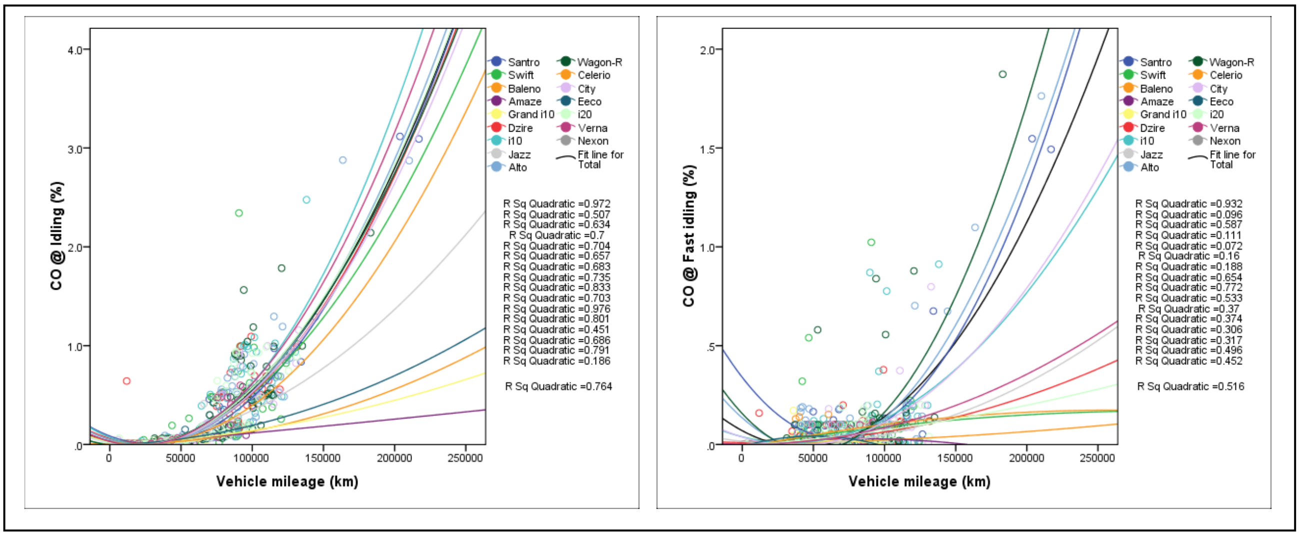


Fig. 4.21 Vehicle mileage vs. CO emission for top 16 models (at idling and fast idling)

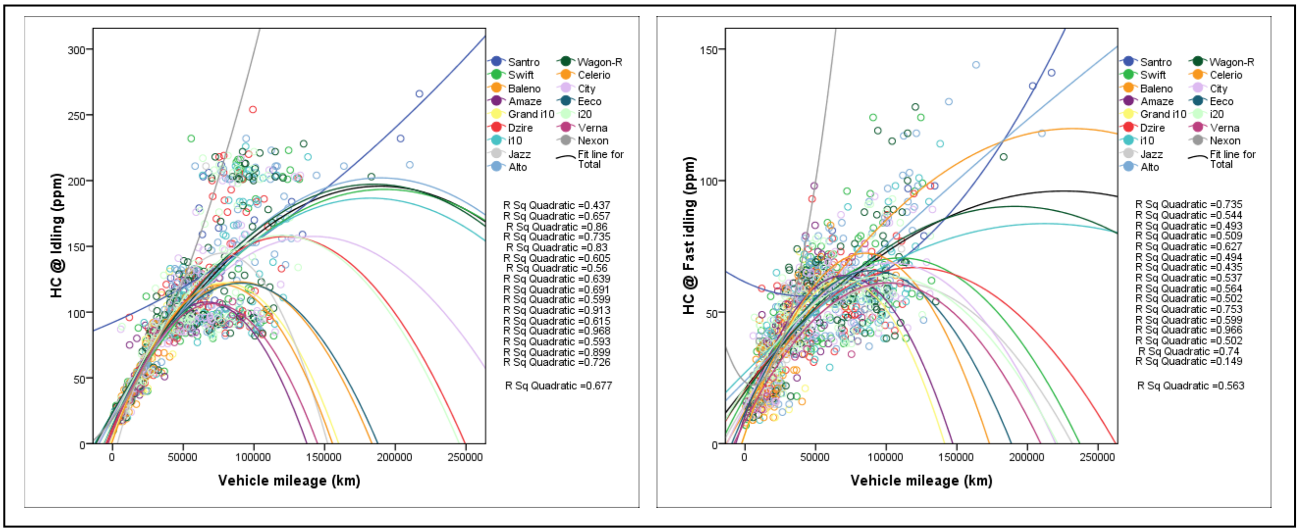


Fig. 4.22 Vehicle mileage vs. HC emission for top 16 models (at idling and fast idling)

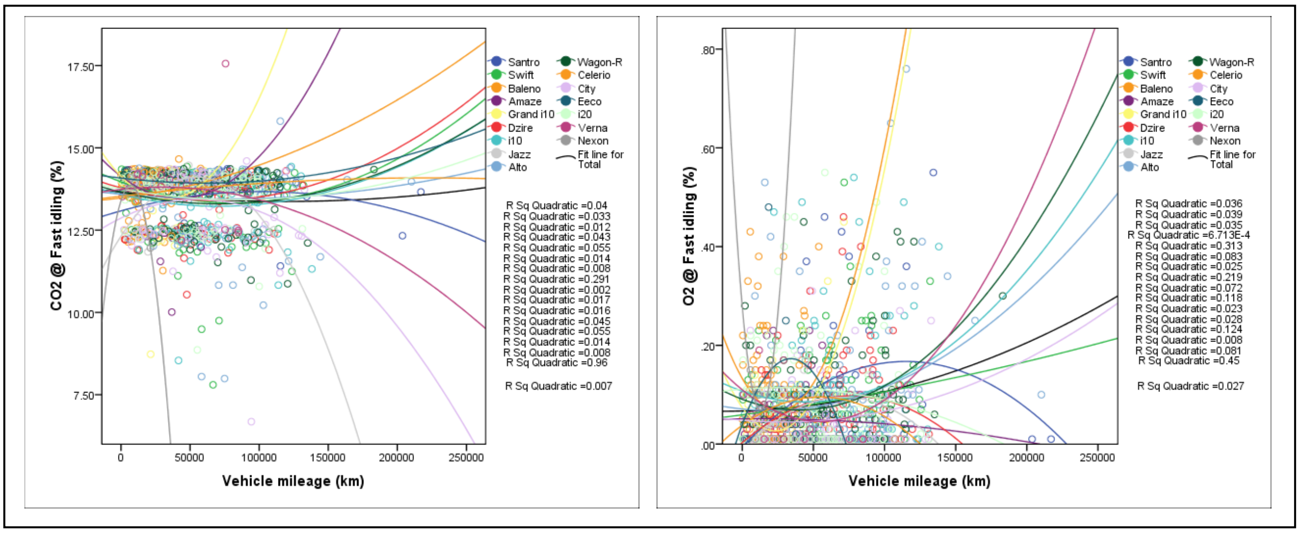


Fig. 4.23 Vehicle mileage vs. CO_2 and O_2 emission for top 16 models (at fast idling)

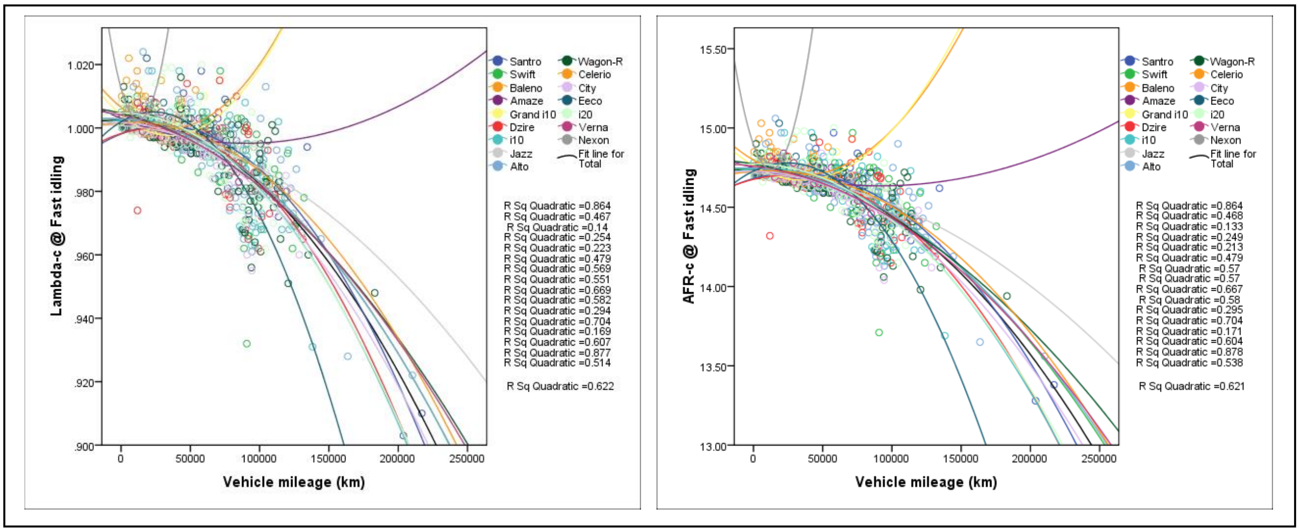


Fig. 4.24 Vehicle mileage vs. λ and AFR for top 16 models (at fast idling)

Table 4.14: Emission equations with respect to vehicle mileage (top 16 models – part 1/4)

Parameter	**Santro**		**Swift**		**Baleno**		**Amaze**	
	Equation	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**
CO @ Idling	$y = 0.00000000009x^2 - 0.00000543404x + 0.0857$	0.972	$y = 0.00000000007x^2 - 0.00000160165x - 0.00035$	0.507	$y = 0.00000000001x^2 - 0.00000017461x + 0.0036$	0.634	$y = 0.0000000000004x^2 + 0.0000012802229x - 0.0158$	0.701
HC @ Idling	$y = 0.000000001x^2 + 0.000474012x + 92.0845$	0.437	$y = -0.000000005x^2 + 0.001790774x + 21.0418$	0.657	$y = -0.000000014x^2 + 0.002504923x + 10.7286$	0.861	$y = -0.00000002x^2 + 0.00286399x + 12.2148$	0.735
CO_2 @ Fast idling	$y = -0.00000000006x^2 + 0.00001159877x + 13.0862$	0.041	$y = 0.0000000001x^2 - 0.0000156774x + 13.9668$	0.033	$y = 0.000000000049x^2 + 0.000005100652x + 13.4769$	0.012	$y = 0.0000000004x^2 - 0.0000319998x + 14.1366$	0.043
O_2 @ Fast idling	$y = -0.00000000001x^2 + 0.00000301910x - 0.0063$	0.036	$y = 0.000000000001x^2 + 0.000000393434x + 0.0592$	0.039	$y = 0.000000000097x^2 - 0.000005052877x + 0.1329$	0.035	$y = -0.000000000001x^2 + 0.000000031485x + 0.05114$	0.006
λ @ Fast idling	$y = -0.000000000003x^2 + 0.000000171842x + 0.9981$	0.864	$y = -0.000000000002x^2 - 0.000000023776x + 1.0026$	0.467	$y = 0.000000000005x^2 - 0.000000357634x + 1.0065$	0.141	$y = 0.000000000001x^2 - 0.000000174545x + 1.0031$	0.254
AFR @ Fast idling	$y = -0.00000000004x^2 + 0.00000247048x + 14.6808$	0.862	$y = -0.00000000003x^2 - 0.00000024596x + 14.7413$	0.468	$y = 0.000000000070x^2 - 0.000005093041x + 14.7982$	0.133	$y = 0.000000000014x^2 - 0.000002491581x + 14.7484$	0.249

Table 4.15: Emission equations with respect to vehicle mileage (top 16 models – part 2/4)

Parameter	**Grand i10**		**Dzire**		**i10**		**Jazz**	
	Equation	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**
CO @ Idling	$y = 0.000000000008x^2 + 0.000000716250x - 0.0076$	0.704	$y = 0.00000000009x^2 - 0.00000413441x + 0.0609$	0.657	$y = 0.0000000001x^2 - 0.0000056763x + 0.0699$	0.683	$y = 0.00000000003x^2 + 0.00000033106x - 0.0171$	0.735
HC @ Idling	$y = -0.00000002x^2 + 0.00295592x + 5.4356$	0.831	$y = -0.00000001x^2 + 0.00238868x + 11.3566$	0.605	$y = -0.000000005x^2 + 0.001786759x + 23.7656$	0.563	$y = -0.00000003x^2 + 0.00406647x - 13.312$	0.639
CO_2 @ Fast idling	$y = 0.0000000007x^2 - 0.0000433359x + 14.1349$	0.055	$y = 0.00000000009x^2 - 0.00001149451x + 13.7810$	0.014	$y = 0.00000000007x^2 - 0.00001006070x + 13.5824$	0.008	$y = -0.0000000006x^2 + 0.0000646939x + 12.3184$	0.291
O_2 @ Fast idling	$y = 0.00000000009x^2 - 0.00000411671x + 0.0739$	0.313	$y = -0.00000000002x^2 + 0.00000247083x + 0.0028$	0.083	$y = 0.00000000001x^2 - 0.00000098482x + 0.1074$	0.025	$y = -0.00000000002x^2 + 0.00000305449x - 0.01376$	0.219
λ @ Fast idling	$y = 0.00000000001x^2 - 0.00000036844x + 1.0042$	0.223	$y = -0.000000000003x^2 + 0.000000136677x + 0.9982$	0.479	$y = -0.000000000003x^2 + 0.000000047241x + 1.0024$	0.569	$y = -0.000000000001x^2 - 0.000000029293x + 1.0007$	0.551
AFR @ Fast idling	$y = 0.00000000007x^2 - 0.00000519762x + 14.7626$	0.213	$y = -0.00000000004x^2 + 0.00000211898x + 14.676$	0.478	$y = -0.00000000004x^2 + 0.00000069178x + 14.7408$	0.571	$y = -0.00000000002x^2 - 0.00000041878x + 14.7160$	0.572

Table 4.16: Emission equations with respect to vehicle mileage (top 16 models – part 3/4)

Parameter	Alto		Wagon-R		Celerio		City	
	Equation	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**
CO @ Idling	$y = 0.0000000001x^2 - 0.0000044515x + 0.0476$	0.833	$y = 0.00000000008x^2 - 0.00000203764x - 0.0081$	0.703	$y = 0.00000000006x^2 - 0.00000284245x + 0.03107$	0.976	$y = 0.00000000008x^2 - 0.00000283997x + 0.01412$	0.801
HC @ Idling	$y = -0.0000000051x^2 + 0.0019314760x + 19.1092$	0.691	$y = -0.000000005x^2 + 0.001881789x + 23.5856$	0.599	$y = -0.00000002x^2 + 0.00306362x + 2.27620653$	0.913	$y = -0.00000001x^2 + 0.00191840x + 21.4148$	0.615
CO_2 @ Fast idling	$y = 0.00000000003x^2 - 0.00000385826x + 13.5920$	0.002	$y = 0.00000000007x^2 - 0.00001004716x + 13.6592$	0.017	$y = -0.00000000001x^2 + 0.00000500685x + 13.5316$	0.016	$y = -0.0000000002x^2 + 0.0000205133x + 12.8683$	0.045
O_2 @ Fast idling	$y = 0.00000000001x^2 - 0.00000029500x + 0.0710$	0.072	$y = 0.00000000001x^2 - 0.00000108677x + 0.0908$	0.118	$y = -0.00000000002x^2 + 0.00000209792x + 0.03805$	0.023	$y = 0.000000000004x^2 - 0.000000252334x +$	0.028
λ @ Fast idling	$y = -0.000000000002x^2 - 0.000000030382x + 1.0029$	0.669	$y = -0.000000000001x^2 - 0.000000107412x + 1.0046$	0.582	$= -0.000000000002x^2 + 0.000000035343x + 1.0017$	0.294	$y = -0.000000000002x^2 - 0.000000016510x + 1.0017$	0.704
AFR @ Fast idling	$y = -0.00000000003x^2 - 0.00000040219x + 14.7463$	0.667	$y = -0.00000000002x^2 - 0.00000154739x + 14.7725$	0.581	$y = -0.00000000003x^2 + 0.00000067284x + 14.7267$	0.295	$y = -0.00000000003x^2 - 0.00000015621x + 14.7274$	0.705

Table 4.17: Emission equations with respect to vehicle mileage (top 16 models – part 4/4)

Parameter	Eeco		i20		Verna		Nexon	
	Equation	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**
CO @ Idling	$y = 0.00000000002x^2 + 0.00000042394x - 0.00356$	0.451	$y = 0.00000000009x^2 - 0.00000299235x + 0.01735$	0.686	$y = 0.0000000001x^2 - 0.0000039222x + 0.03110$	0.791	$y = -0.00000000001x^2 + 0.00000045092x + 0.000096$	0.186
HC @ Idling	$y = -0.00000001x^2 + 0.00235900x + 14.9939$	0.968	$y = -0.00000001x^2 + 0.00237894x + 16.3578$	0.593	$y = -0.00000002x^2 + 0.00275248x + 8.8405$	0.899	$y = 0.00000001x^2 + 0.00140749x + 19.0184$	0.726
CO_2 @ Fast idling	$y = 0.00000000004x^2 - 0.00000489751x + 14.0802$	0.055	$y = 0.00000000004x^2 - 0.00000773966x + 13.7559$	0.014	$y = -0.00000000008x^2 + 0.00000467815x + 13.7378$	0.008	$y = -0.000000009x^2 + 0.000133071x + 13.3967$	0.961
O_2 @ Fast idling	$y = -0.0000000001x^2 + 0.0000078155x + 0.0398$	0.124	$y = -0.000000000005x^2 + 0.000000242492x + 0.1112$	0.008	$y = 0.00000000002x^2 - 0.00000234598x + 0.10994$	0.081	$y = 0.000000001x^2 - 0.000032896x + 0.2786$	0.451
λ @ Fast idling	$y = -0.000000000006x^2 + 0.000000261702x + 1.0019$	0.169	$y = -0.000000000002x^2 + 0.000000000699x + 1.0047$	0.607	$y = -0.000000000001x^2 - 0.000000093164x + 1.0041$	0.877	$y = 0.00000000006x^2 - 0.00000157406x + 1.0125$	0.514
AFR @ Fast idling	$y = -0.00000000009x^2 + 0.00000423180x + 14.7281$	0.171	$y = -0.00000000004x^2 + 0.00000001639x + 14.7731$	0.604	$y = -0.00000000002x^2 - 0.00000107894x + 14.7595$	0.878	$y = 0.000000001x^2 - 0.000024764x + 14.8948$	0.538

A glance at emission equations having vehicle mileage as an independent variable finds that the accumulated kilometers (mileage) of cars has a direct impact on the emission characteristics or parameters. Higher vehicle mileage over a period of time may also render a vehicle non-compliant towards extant emission norms. This non-compliance may need to be addressed either by way of a quick-fix or thorough maintenance, in a bid to bringing the vehicle back to compliance level. Although a data scattering may be observed in fast idling conditions for both CO and HC (Fig. 4.13, 4.14 and Table 4.12) resulting in a poor correlation value ranging between 0.5 and 0.6, it is slightly better compared to those reported in the case of vehicle age.

The emission equations calculated for the top 3 makes are generally in line with those for the whole data set except for HCIL make depicting a poor or no correlation while comparing vehicle mileage vs. Fast idling CO ($R^2 = 0.295$). This scenario is the same as found in the case of vehicle age. A further look at the model-wise case for the top 16 models revealed almost no correlation scenario for mileage vs. CO @ Fast idling, for e.g., Swift, Amaze, Grand i10, Dzire, i10 ($R^2 < 0.1$), whereas Celerio, City, Eeco and i20 fared with a poor correlation ($R^2 < 0.3$). While the reason behind such poor correlation can be explained by the difficulty in attaining and maintaining the high idle conditions, many instances of no correlation need to be checked with a greater number of samples.

The study further indicated that CO_2 and O_2 exhaust concentrations do not seem to be affected by the vehicle mileage for fast idling conditions for all the analysis cases, i.e., entire data set, top 3 makes and top 16 models. (Figs.4.15, 4.19 and 4.23; Tables 4.12 – 4.17) whereas λ and AFR @ fast idling were found to be fairly correlated with vehicle mileage (Figs. 4.16, 4.20 and 4.24; Tables 4.12 – 4.17). A comparison of emission equations along with correlation coefficients for different dataset conditions is presented in Table 4.18.

Table 4.18: Emission equations for different datasets with respect to vehicle mileage

Data set	**Entire (n=1580)**		**Top 3 makes (n=1321)**		**Top 16 models (n=1115)**	
Parameters	**Equation**	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**
CO @ Idling	$y = 0.0000000001x^2 - 0.0000037836x + 0.0346$	0.748	$y = 0.000000000092x^2 - 0.000003940174x + 0.0369$	0.772	$y = 0.0000000001x^2 - 0.0000035432x + 0.0315$	0.764
CO @ Fast idling	$y = 0.0000000001x^2 - 0.0000044730x + 0.0801$	0.557	$y = 0.000000000053x^2 - 0.000004570650x + 0.0819$	0.595	$y = 0.00000000005x^2 - 0.00000386539x + 0.0698$	0.516
HC @ Idling	$y = -0.0000000047x^2 + 0.0018247565x + 21.6145$	0.671	$y = -0.0000000045x^2 + 0.0018091474x + 22.2022$	0.682	$y = -0.000000005x^2 + 0.001840519x + 21.6435$	0.677
HC @ Fast idling	$y = -0.0000000011x^2 + 0.0006223787x + 21.8187$	0.551	$y = -0.00000000091x^2 + 0.00060544885x + 22.4082$	0.564	$y = -0.000000001x^2 + 0.000662928x + 21.1604$	0.563
CO_2 @ Fast idling	$y = 0.00000000001x^2 - 0.00000366929x + 13.6214$	0.007	$y = 0.000000000012x^2 - 0.000003064650x + 13.5956$	0.004	$y = 0.00000000002x^2 - 0.00000474054x + 13.652$	0.007
O_2 @ Fast idling	$y = 0.000000000004x^2 - 0.000000045484x + 0.0741$	0.026	$y = 0.0000000000037x^2 + 0.0000000689162x + 0.0652$	0.039	$y = 0.000000000003x^2 + 0.000000091726x + 0.06710$	0.027
λ @ Fast idling	$y = -0.000000000002x^2 - 0.000000004131x + 1.0027$	0.622	$y = -0.0000000000021x^2 + 0.0000000061516x + 1.0022$	0.647	$y = -0.000000000002x^2 - 0.000000006217x + 1.0025$	0.622
AFR @ Fast idling	$y = -0.00000000003x^2 - 0.00000000697x + 14.7436$	0.621	$y = -0.000000000031x^2 + 0.000000141300x + 14.7357$	0.646	$y = -0.00000000003x^2 - 0.00000004167x + 14.740$	0.621

An overview of the graphs and the tables on emission equations gives a glimpse of how the trendlines for the top 3 makes and top 16 models stand, basis their representation in the entire data set. Considering the trendlines to be the guiding factor, the relative standing of different makes and models in terms of their idle CO and HC emissions (in both testing modes) due to accumulated mileage is presented in Tables 4.19 and 4.20.

Table 4.19: Relative standing of different makes in descending order in terms of their CO and HC emissions due to mileage

S. No.	Mileage effect on CO emission		Mileage effect on HC emission	
	Idling	Fast idling	Idling	Fast idling
1.	MSIL	MSIL	HMIL	HMIL
2.	HMIL	HMIL	MSIL	MSIL
3.	HCIL	HCIL	HCIL	HCIL

Table 4.20: Relative standing of different models in descending order in terms of their CO and HC emissions due to mileage

S. No.	Mileage effect on CO emission			Mileage effect on HC emission		
	Idling	Fast idling	Change in standing	Idling	Fast idling	Change in standing
1.	i10	Wagon-R	↑	Nexon	Nexon	↔
2.	Verna	Alto	↑	Santro	Santro	↔
3.	Alto	Santro	↑	Alto	Alto	↔
4.	i20	City	↑	Swift	Baleno	↑
5.	Jazz	i10	↓	Wagon-R	Wagon-R	↔
6.	Santro	Verna	↓	i10	i10	↔
7.	Dzire	Nexon	↑	City	Dzire	↑
8.	Wagon-R	Dzire	↓	Dzire	Swift	↓
9.	City	i20	↓	i20	Jazz	↑
10.	Swift	Baleno	↑	Eeco	i20	↓
11.	Baleno	Swift	↓	Baleno	City	↓
12.	Nexon	Celerio	↑	Grand i10	Verna	↑
13.	Eeco	Amaze	↑	Celerio	Eeco	↓
14.	Celerio	i20	↓	Jazz	Celerio	↓
15.	Grand i10	Eeco	↓	Verna	Amaze	↑
16.	Amaze	Grand i10	↓	Amaze	Grand i10	↓

↓ *= standing down from earlier position* ↑ = *standing up from earlier position* ↔ *= no change from earlier position*

4.1.1.3 Vehicle body type

Three different body types were encountered in the present study, i.e., Hatchback, Sedan and SUV (Sports Utility Vehicles) for different vehicle classes. In view of no definitive trend observed using scatter plots, an attempt was made to understand the varying degree of tailpipe emission and parameters vis-à-vis vehicle body type using boxplots. The same for various variables in relation to vehicle body types are presented in Figures 4.25 – 4.28 for whole dataset, Figures 4.29 – 4.32 for the top 3 makes and in Figures 4.33 – 4.36 for the top 16 models. It is seen that the range of CO and HC emission (in both test conditions) is relatively higher in the case of hatchbacks and sedans compared to SUVs. Although the outlier values are found to be maximum for hatchbacks, slightly lower for sedans and minimum for SUVs, an indication of such pattern may have been the number of subgroup samples in the overall number of vehicles attended. However, it can still be interpreted that SUVs have relatively lesser emissions of both CO and HC in both testing conditions. A scope of refinement in this finding lies in the sense that a larger data set might throw some more light on how emission ranges can be a little more definitive and freer from outliers considering vehicle body type as an independent variable.

The top 3 makes and top 16 models also followed the CO and HC emission ranges as in the case of the entire data. HMIL and MSIL were found to exhibit similar emission ranges across all body types, while HCIL seemed to have a lesser range of values for both CO and HC emissions under both testing conditions. MSIL in SUV body type has a relatively higher emission of CO and HC both under idle and fast idle testing conditions. Santro, i10, Alto, and Wagon-R models reported a relatively higher range of CO in both idling and fast idling conditions in the hatchback category followed by Dzire, City and Verna in the sedan category. SUVs of all models depicted the lowest ranges with almost all of them complying with the in-use exhaust emission norms. HC for all models in idle testing reported ranges between 10 ppm to 200 ppm with many outliers (between 200 – 250 ppm) in both hatchback and sedan categories. Generally, the fast-idle testing modes returned lower values for both CO and HC emissions backed by the fact that at higher engine speed, a relatively better AFR in combustion chamber led to better burning of fuel and thereby lesser CO and HC in the exhaust. Values of other parameters (CO_2, O_2, λ and AFR) tested in the study compared to vehicle body type did not support any reliable trend to draw any conclusion.

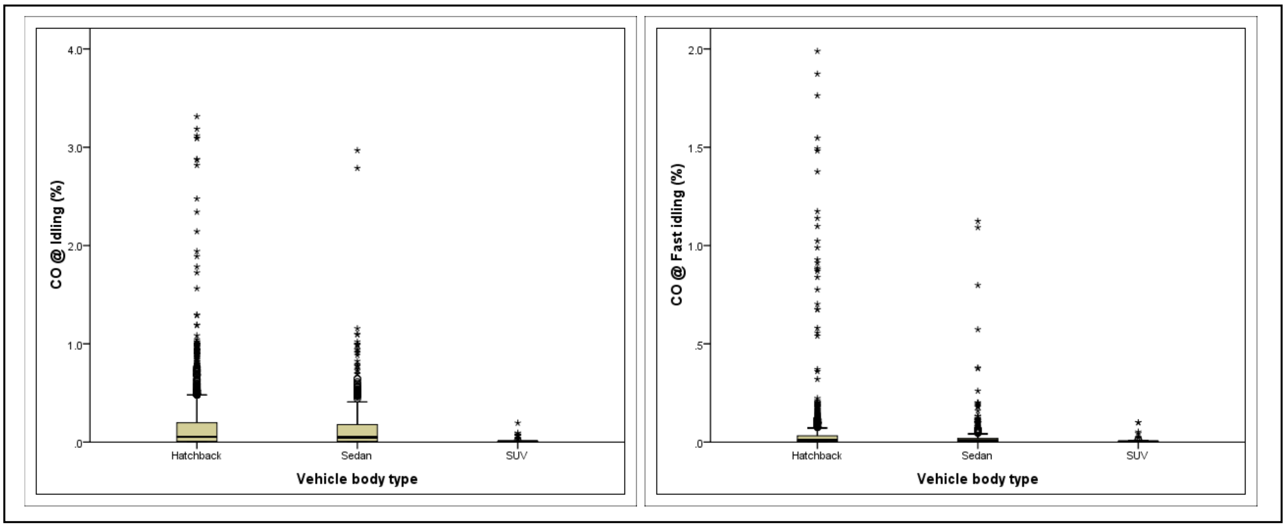


Fig. 4.25 Vehicle body type vs. CO emission (at idling and fast idling)

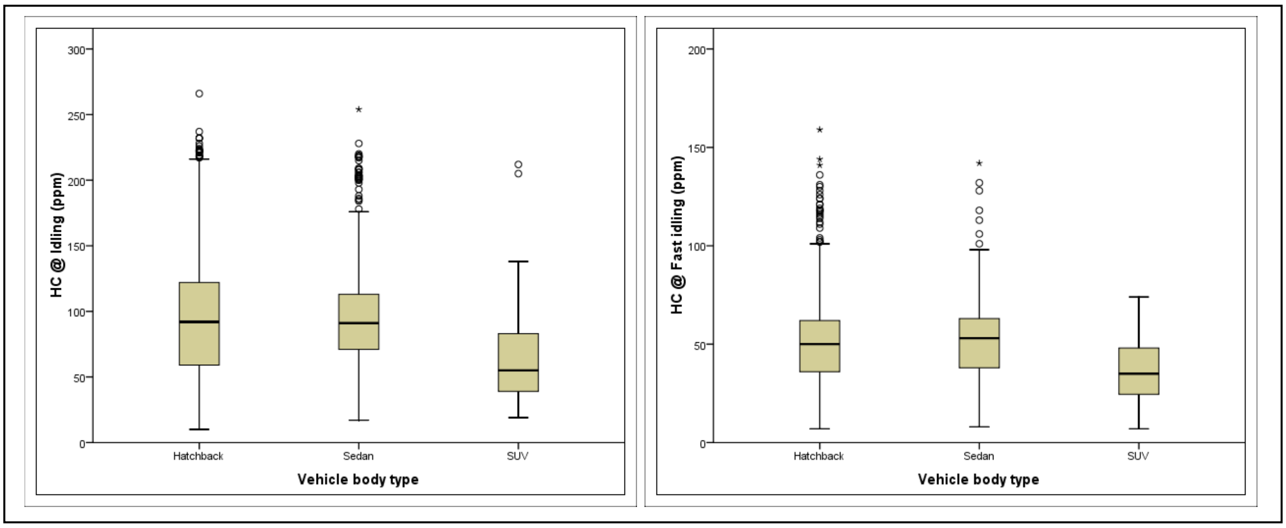


Fig. 4.26 Vehicle body type vs. HC emission (at idling and fast idling)

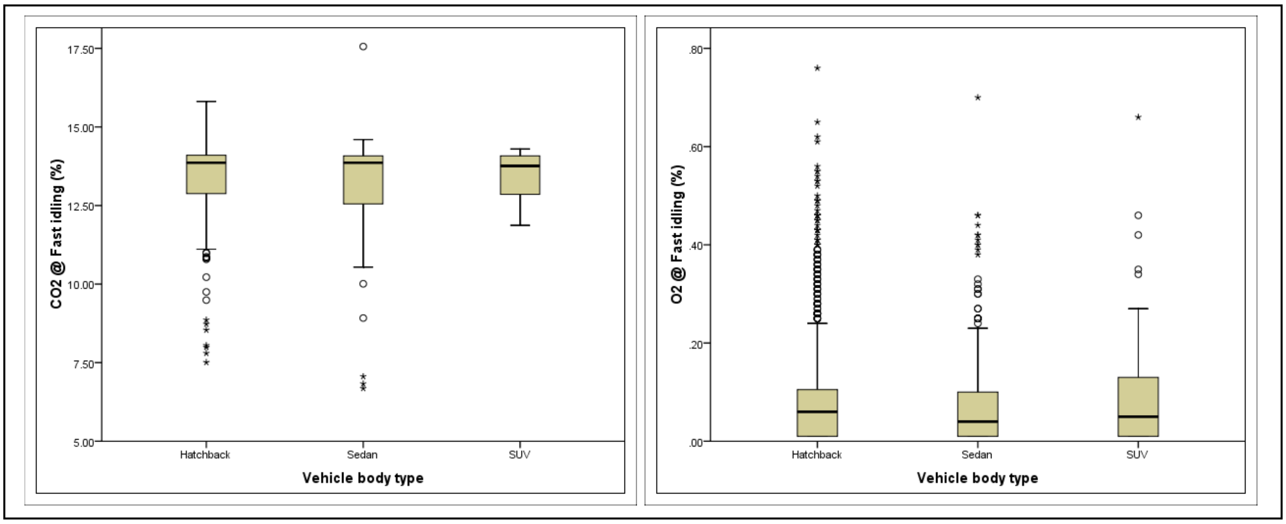


Fig. 4.27 Vehicle body type vs. CO_2 and O_2 emissions (at fast idling)

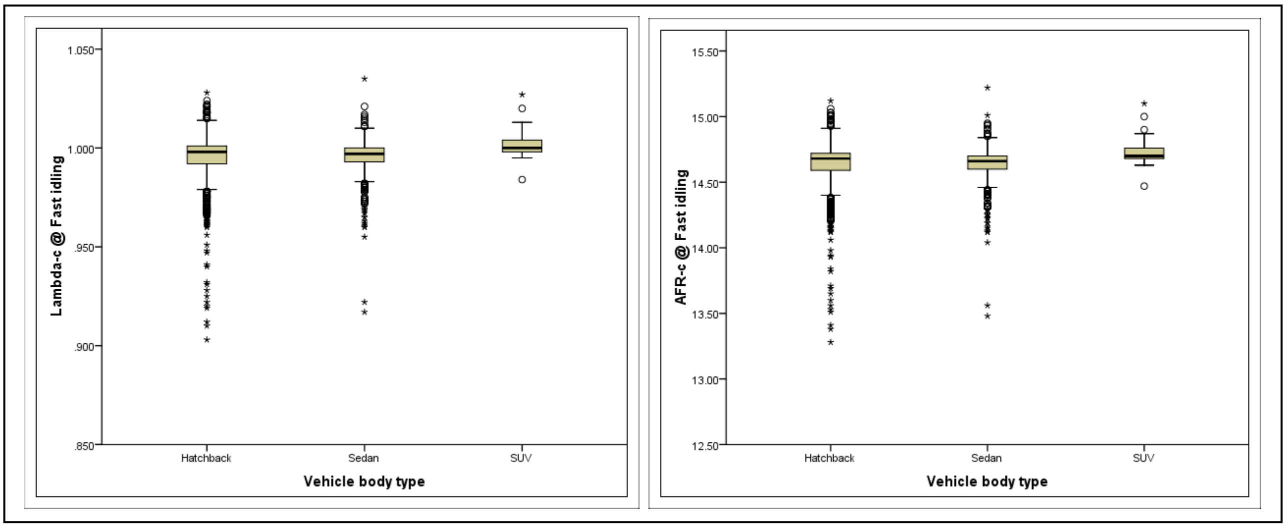


Fig. 4.28 Vehicle body type vs. λ and AFR (at fast idling)

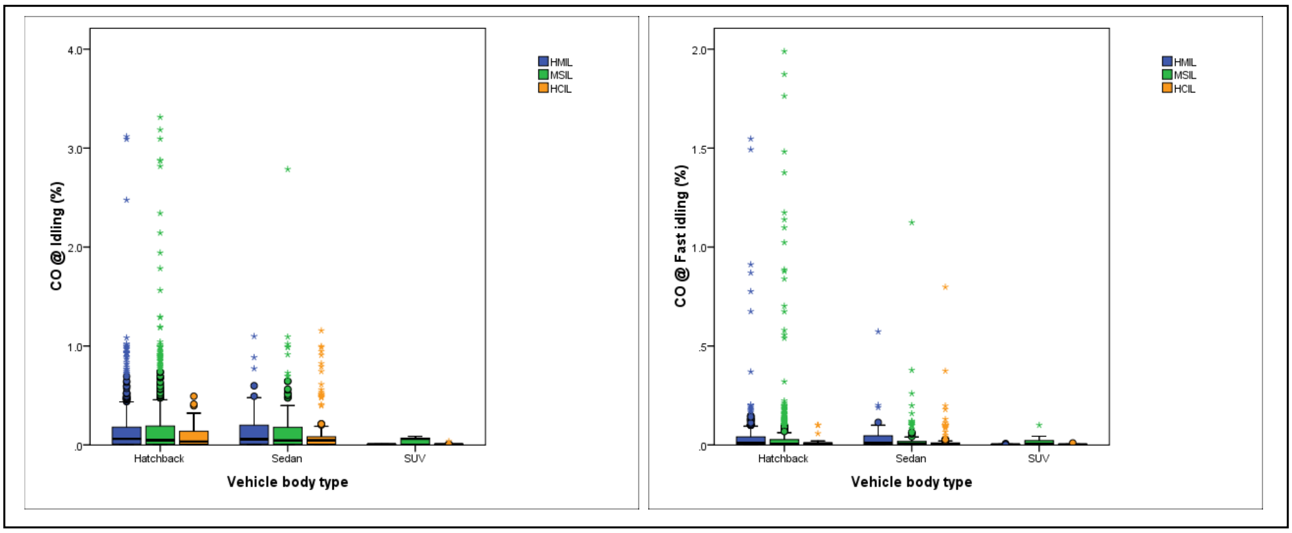


Fig. 4.29 Vehicle body type vs. CO emission for top 3 makes (at idling and fast idling)

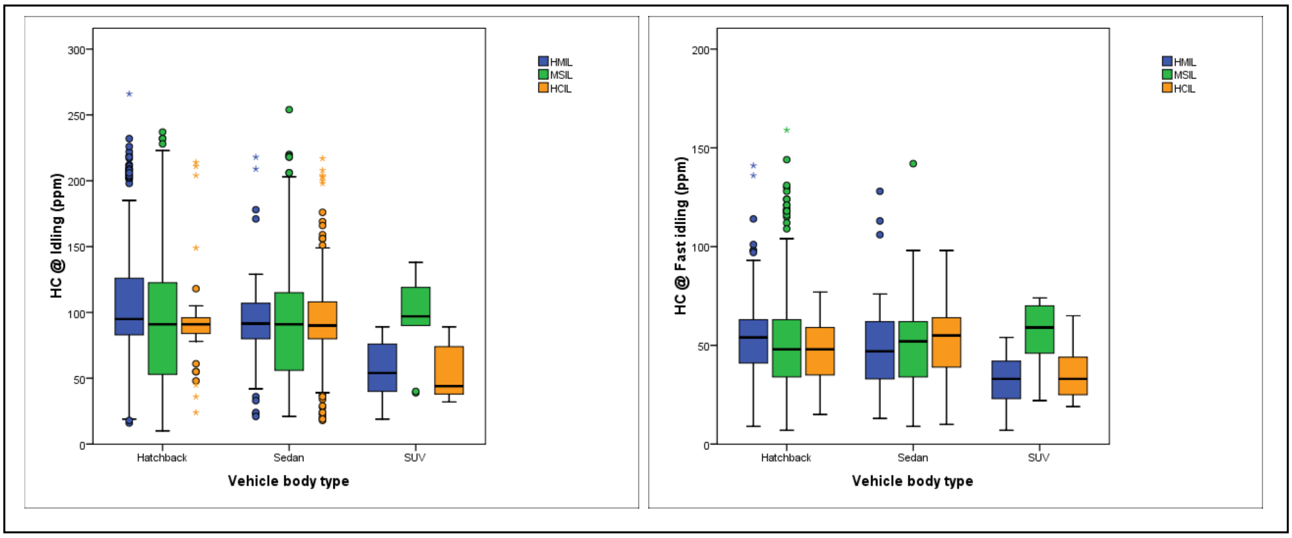


Fig. 4.30 Vehicle body type vs. HC emission for top 3 makes (at idling and fast idling)

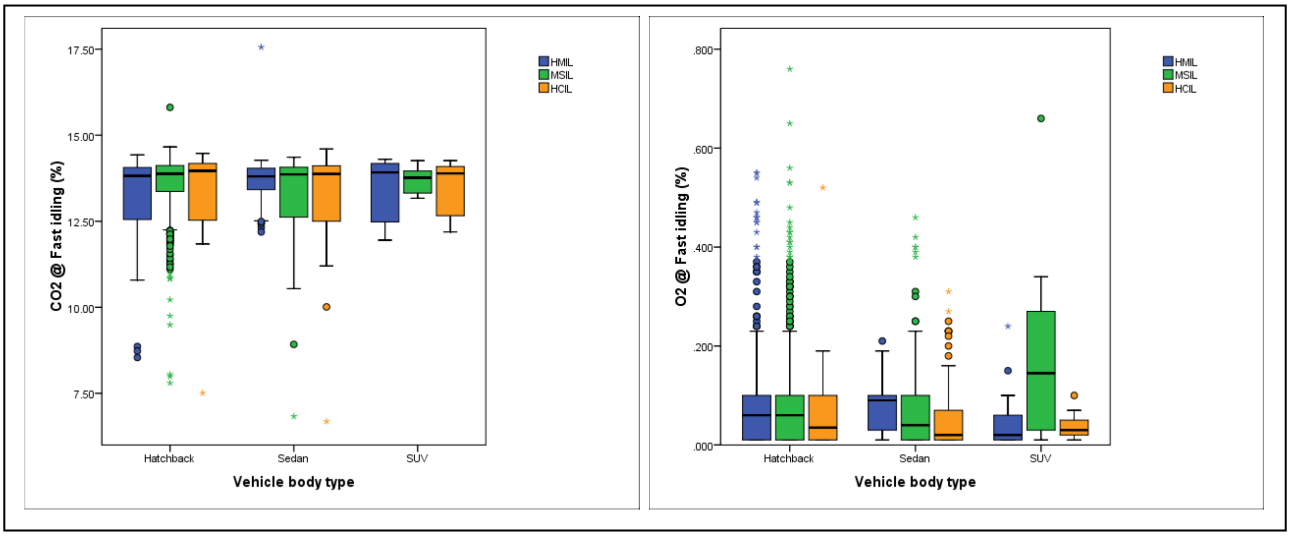


Fig. 4.31 Vehicle body type vs. CO_2 and O_2 emission for top 3 makes (at fast idling)

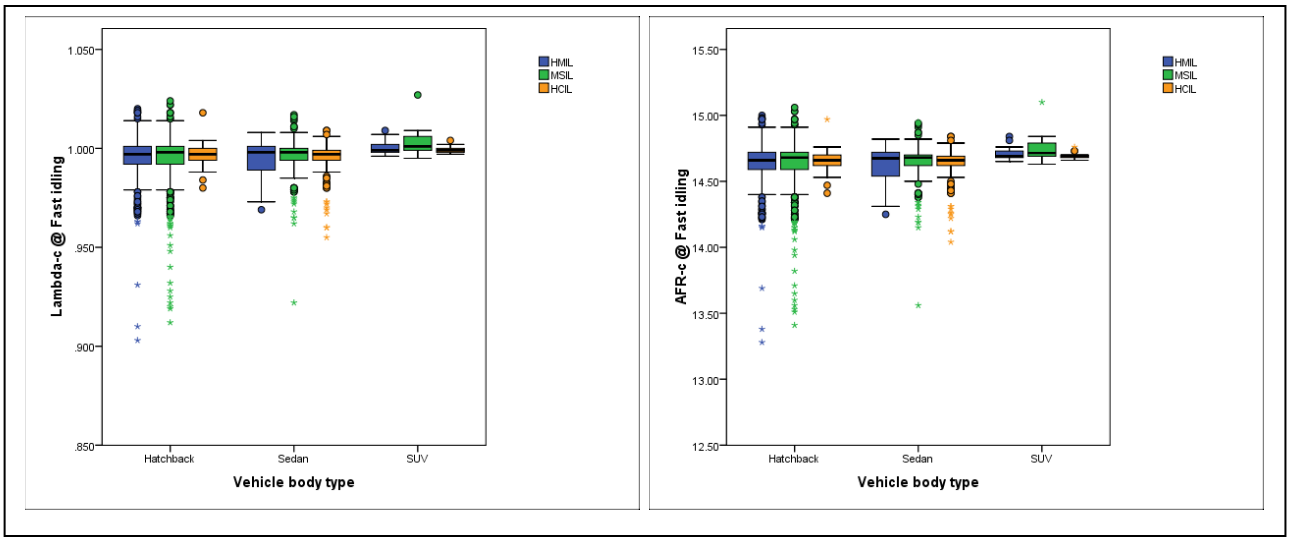


Fig. 4.32 Vehicle body type vs. λ and AFR for top 3 makes (at fast idling)

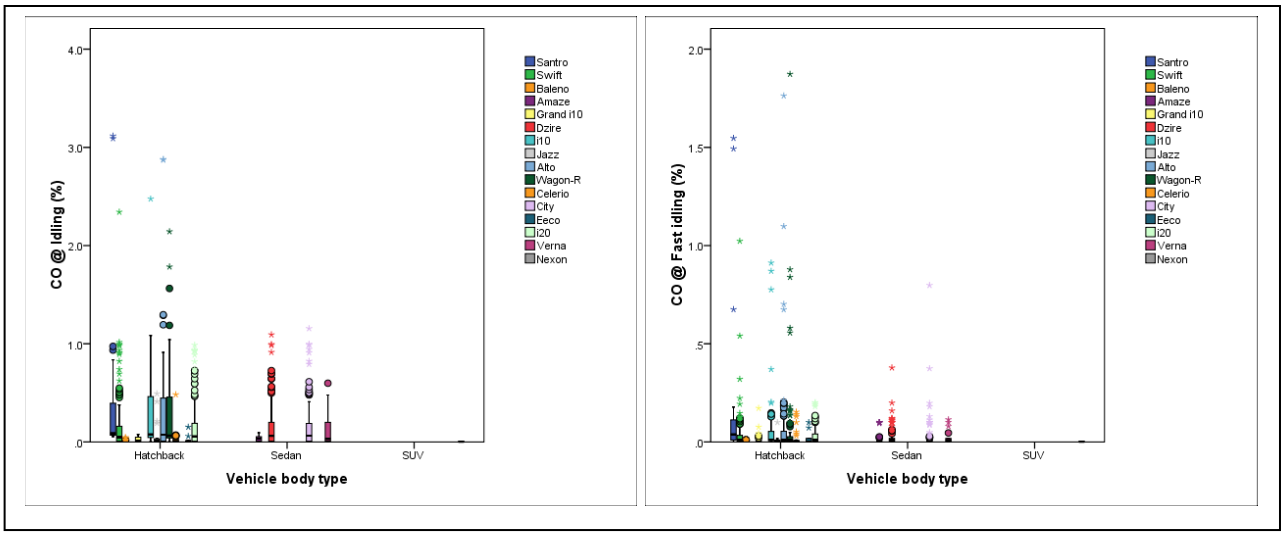


Fig. 4.33 Vehicle body type vs. CO emission for top 16 models (at idling and fast idling)

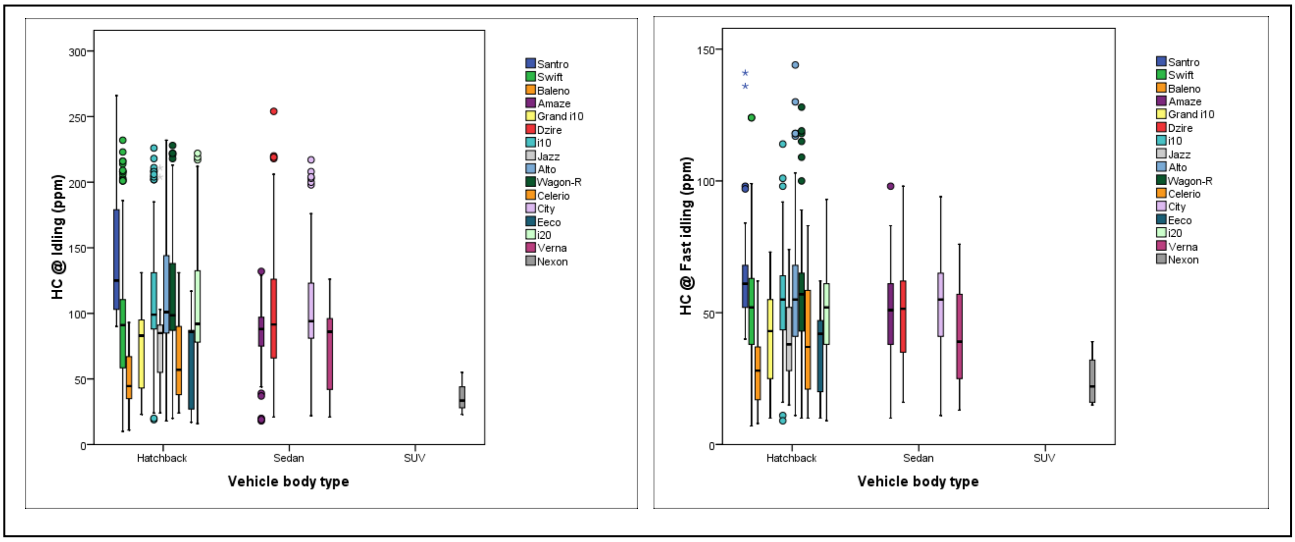


Fig. 4.34 Vehicle body type vs. HC emission for top 16 models (at idling and fast idling)

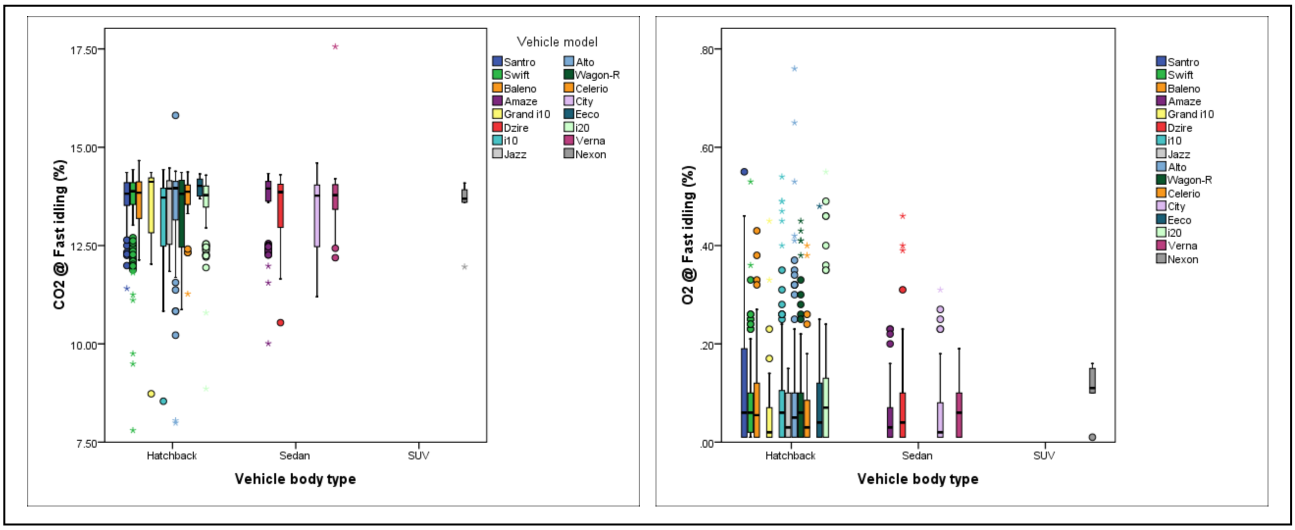


Fig. 4.35 Vehicle body type vs. CO_2 and O_2 emission for top 16 models (at fast idling)

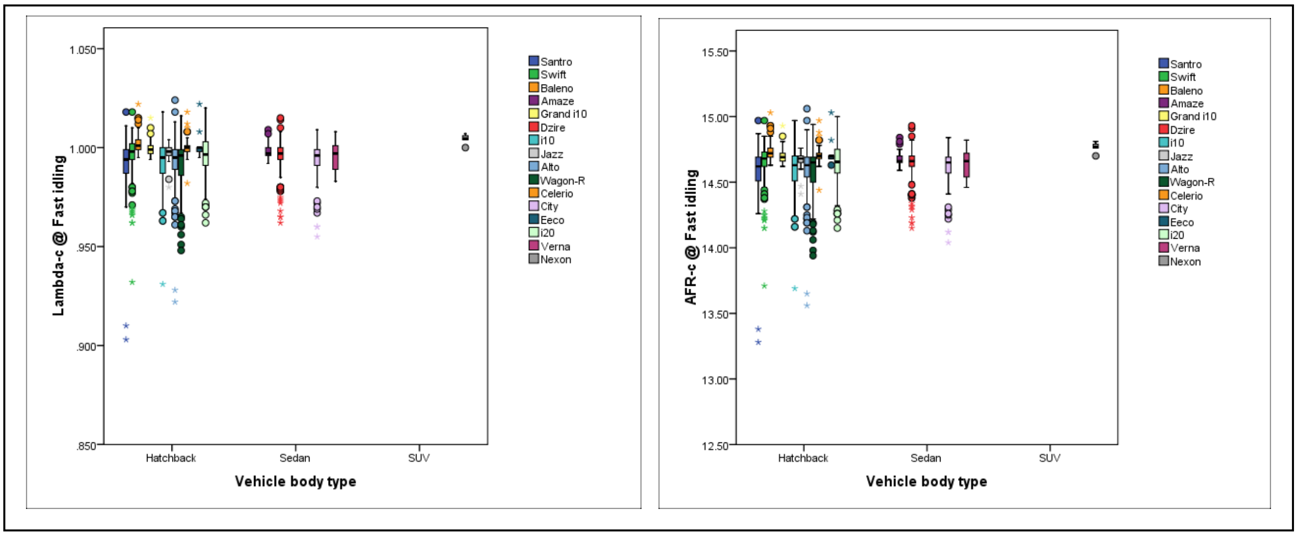


Fig. 4.36 Vehicle body type vs. λ and AFR for top 16 models (at fast idling)

4.1.1.4 Status of vehicle registration life half-past

The registration life for new vehicles in most countries is 15 (fifteen) years from the date of registration with motor vehicle licensing authorities. As it is believed that new vehicles coming out of the plant or factory, will certainly comply with the emission norms; however, once registered, and put into operation, several factors contribute to their deteriorating degree of compliance to the extant emission standards, such as, age, mileage, road conditions, driving behavior, fuel specifications, loading, maintenance criteria and other vehicle-related parameters. From the perspective that an older vehicle may not perform towards its compliance to the norms as the new one, it could be interesting to ascertain, such compliance of vehicles after they pass half of their registration life (7.5 – seven and half years from the date for registration). In this regard, the present study investigated vehicles' performance as to how tailpipe parameters behaved after registration life went half past.

The boxplots depicting the ranges across all tailpipe parameters in relation to the status of registration lift half-past are presented in Figures 4.37 – 4.40 for the whole dataset, Figures 4.41 – 4.44 for the top 3 makes and in Figures 4.45 – 4.48, for the top 16 models. The data analysis revealed that for all the vehicles, makes and models which had completed their half-life of registration, the CO emission in both test conditions, was generally found to be higher compared to those which did not. Such vehicles also were, generally, found to be non-compliant to the exhaust emission norms concerning idling and fast idling CO (0.3 and 0.2 % mass concentration) reporting higher values. The same was the case with regard to HC emission; however, the testing condition, per se, did not make any difference to the data points (i.e., idle and fast idle HC values did not vary much) as the vehicle with registration life half over, returned higher values of HC compared to those which were below 7.5 years of benchmark. Further, the λ and AFR reported reduced values in respect of registration life status (higher for the vehicles which crossed half the registration life and lower for the vehicles which were yet to cross 7.5 years of registration) whereas CO_2 and O_2 emission was found to be not affected by such registration status criteria. Looking into makes and model-wise analysis, it was found that makes and models followed the emission patterns as revealed in the case of the whole dataset, however, Santro, i10, i20 of HMIL, Swift, Alto, Wagon-R of MSIL and City of HCIL make showed relatively higher variation in data points compared to other models.

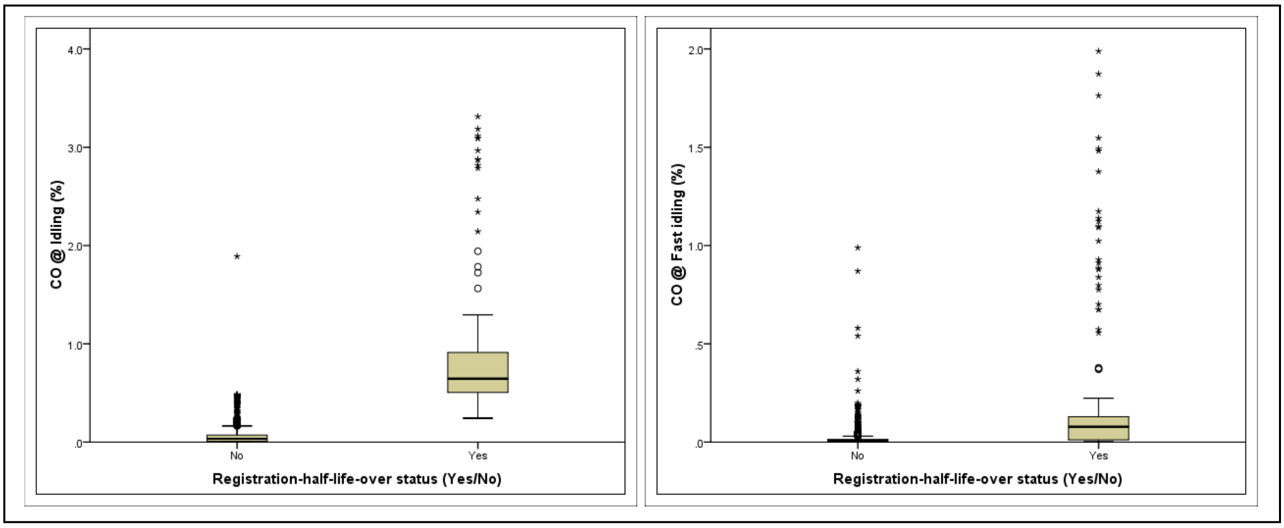


Fig. 4.37 Vehicle registration life vs. CO emission (at idling and fast idling)

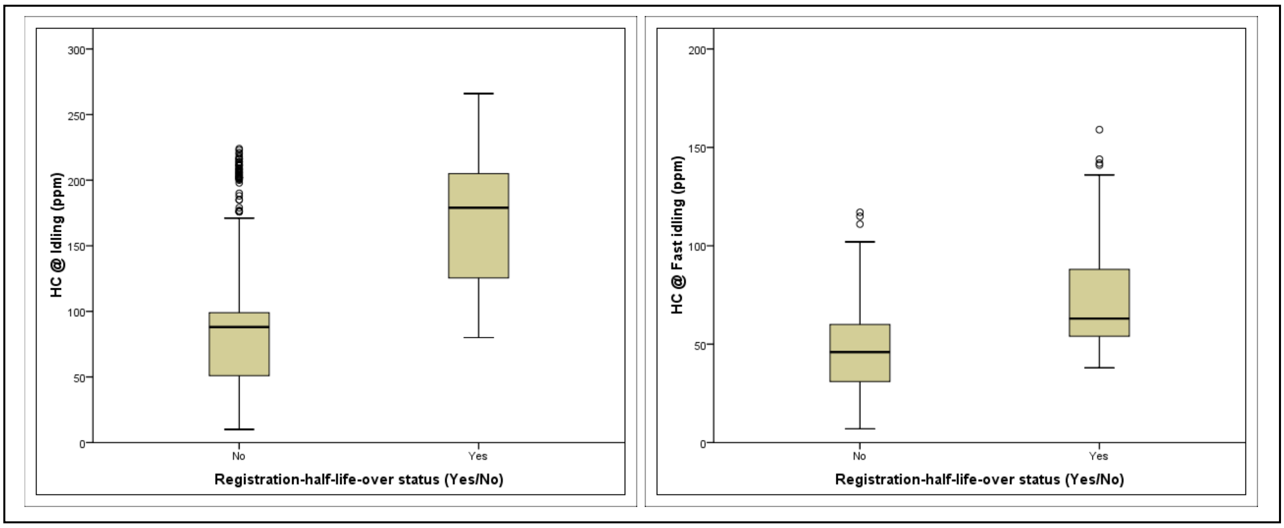


Fig. 4.38 Vehicle registration life vs. HC emission (at idling and fast idling)

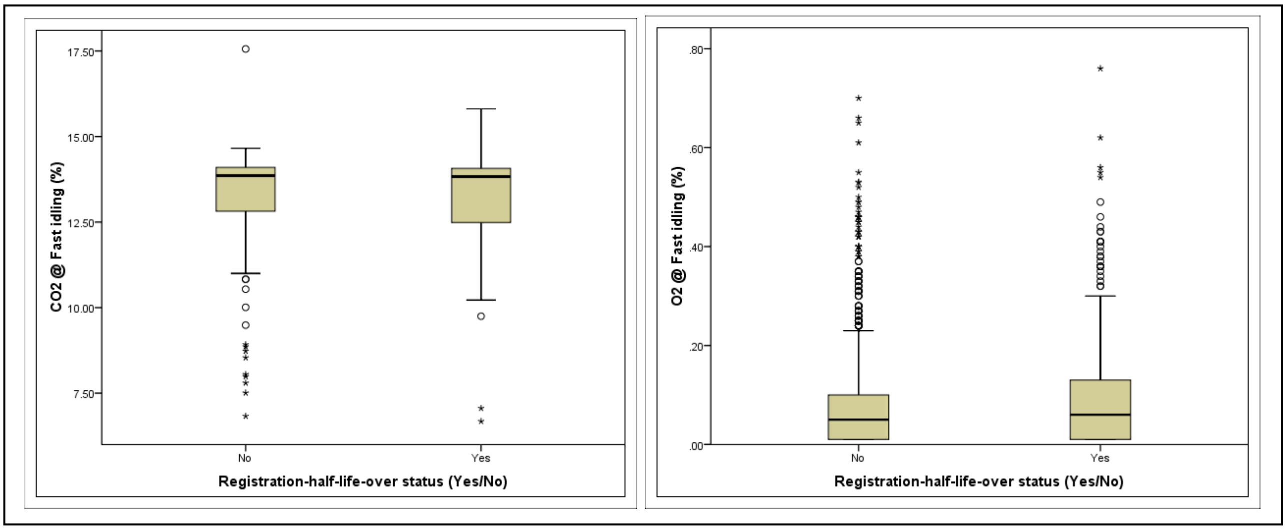


Fig. 4.39 Vehicle registration life vs. CO_2 and O_2 emissions (at fast idling)

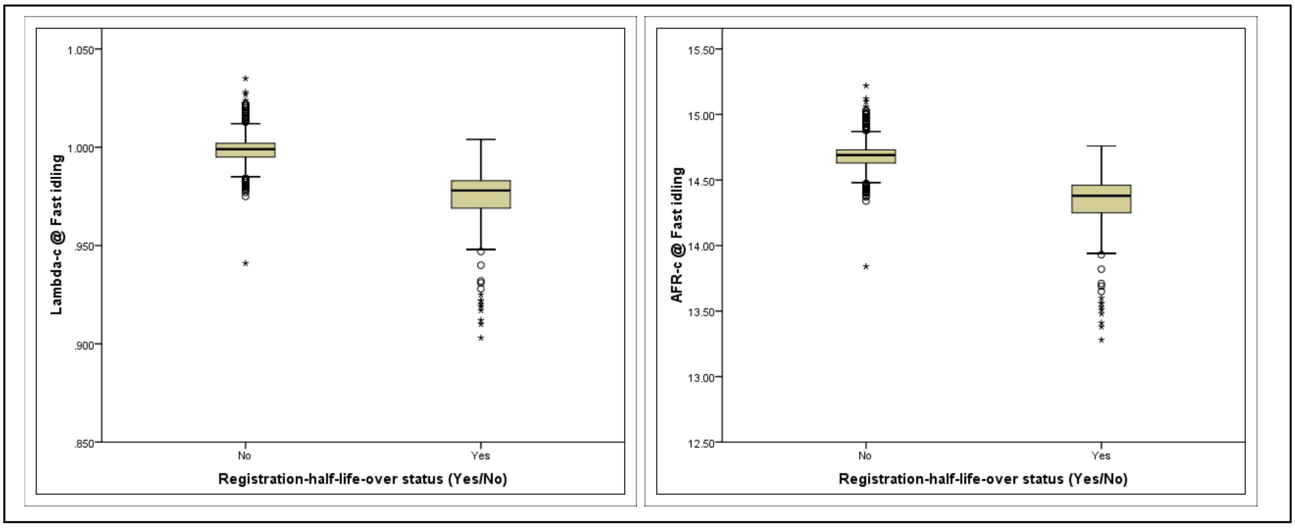


Fig. 4.40 Vehicle registration life vs. λ and AFR (at fast idling)

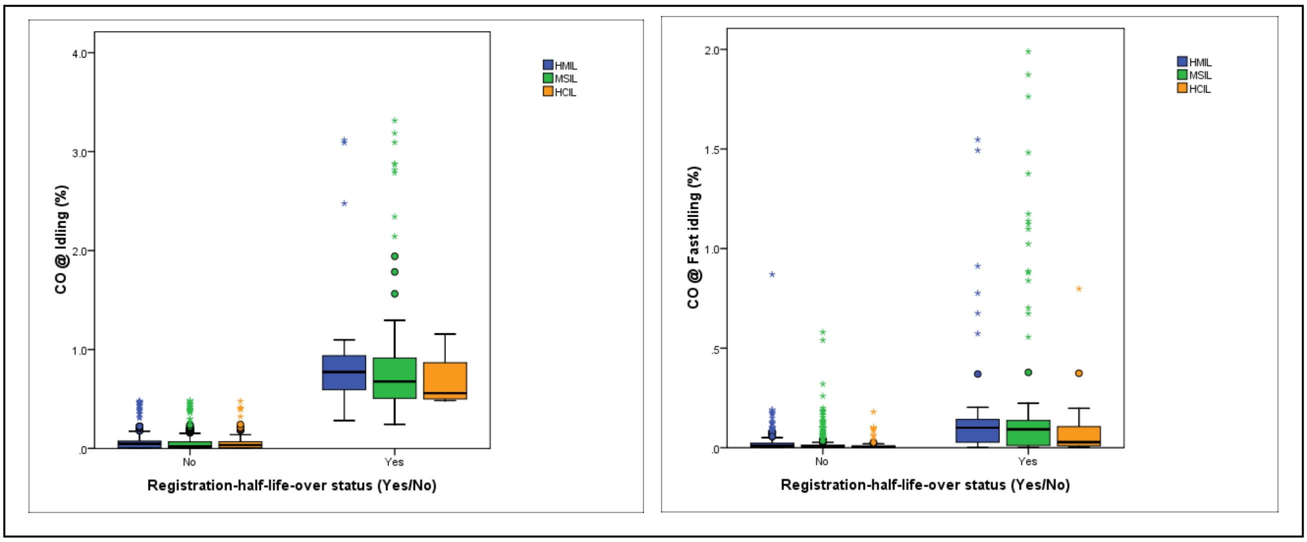


Fig. 4.41 Vehicle regn. life vs. CO emission for top 3 makes (at idling and fast idling)

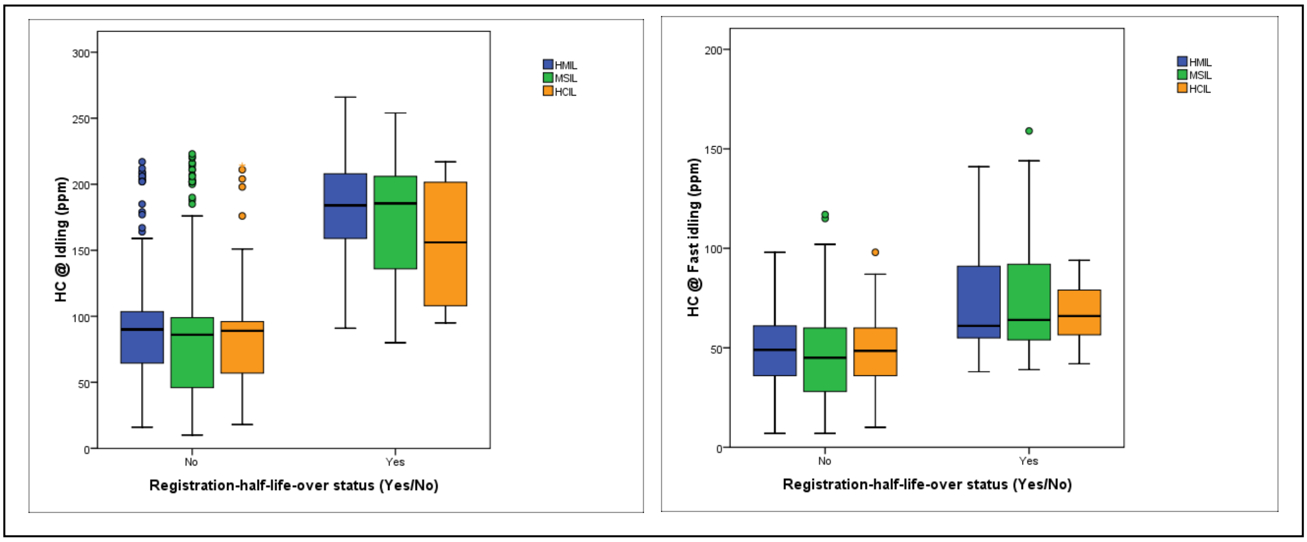


Fig. 4.42 Vehicle regn. life vs. HC emission for top 3 makes (at idling and fast idling)

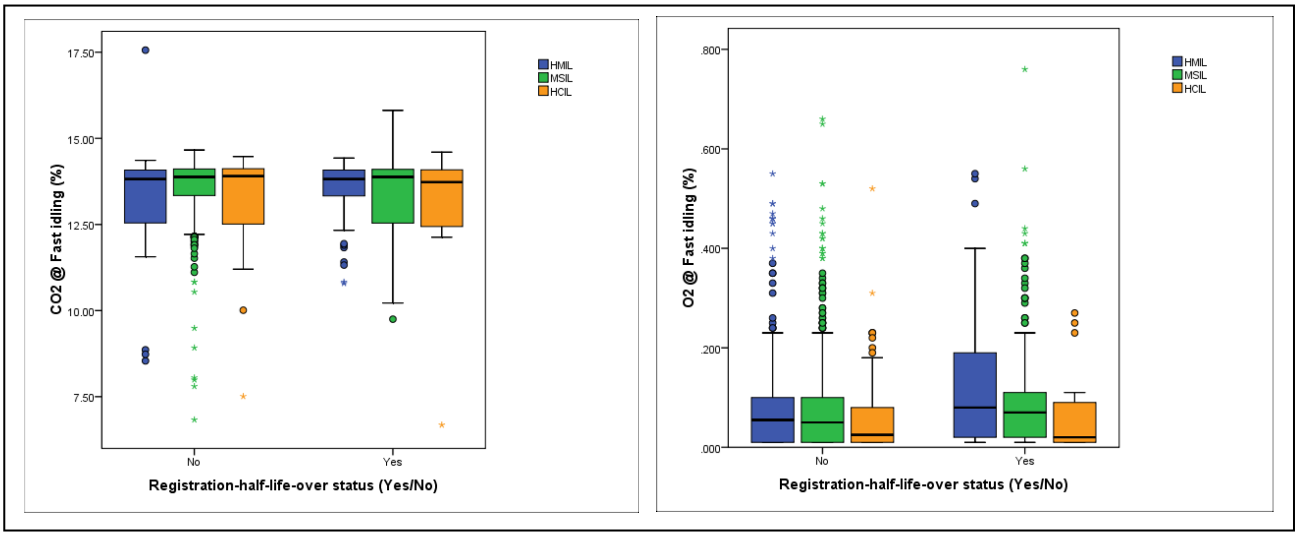


Fig. 4.43 Vehicle regn. life vs. CO_2 and O_2 emission for top 3 makes (at fast idling)

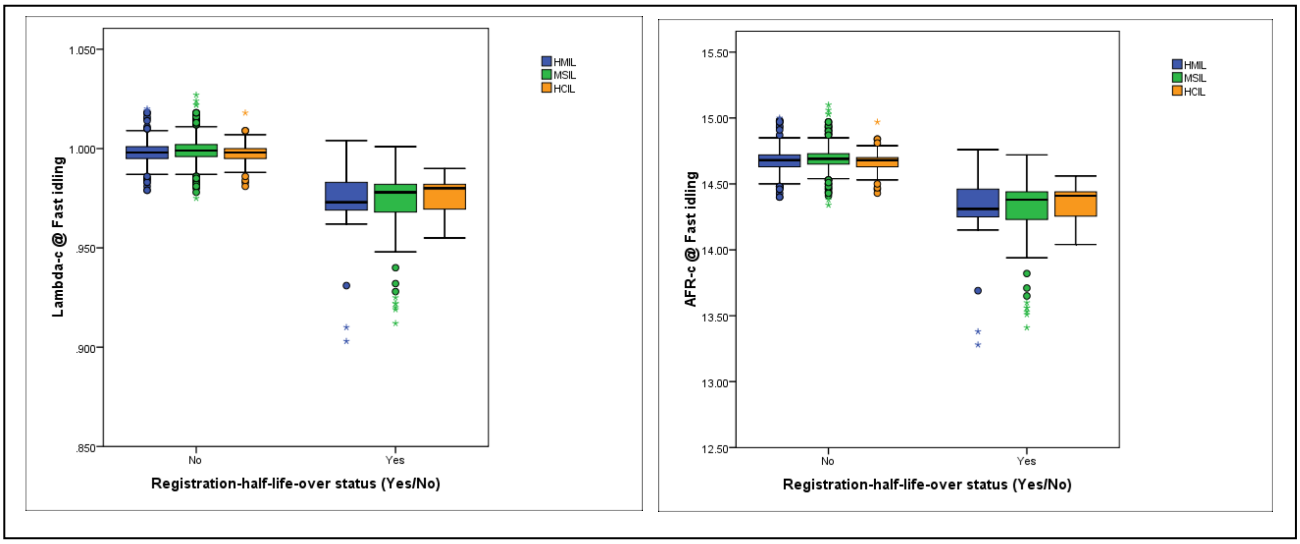


Fig. 4.44 Vehicle regn. life vs. λ and AFR for top 3 makes (at fast idling)

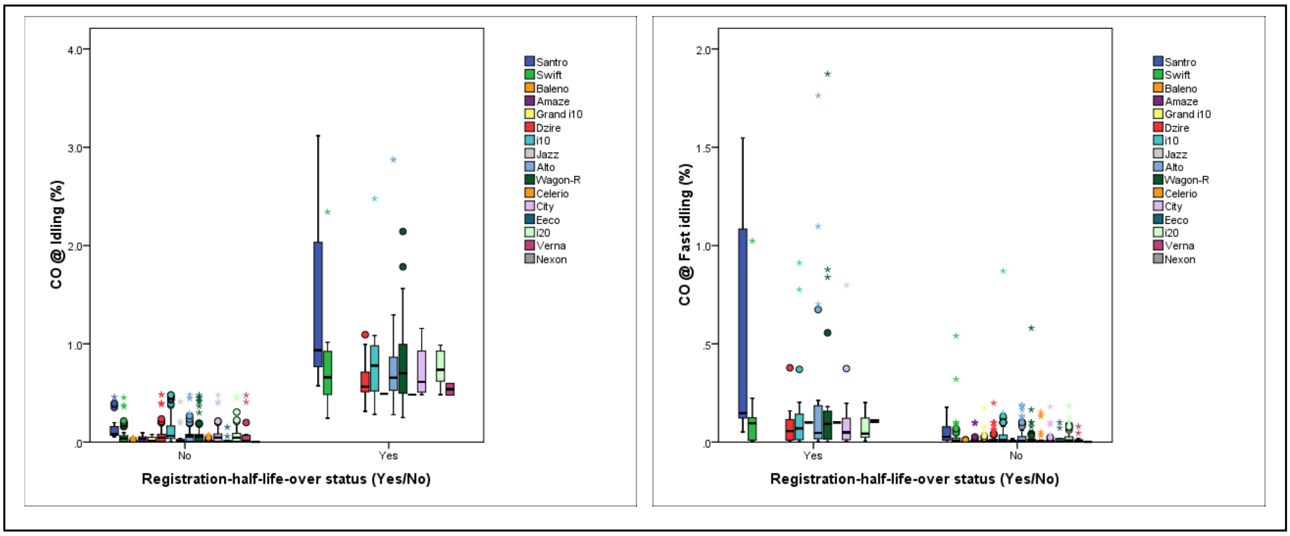


Fig. 4.45 Vehicle regn. life vs. CO emission for top 16 models (at idling and fast idling)

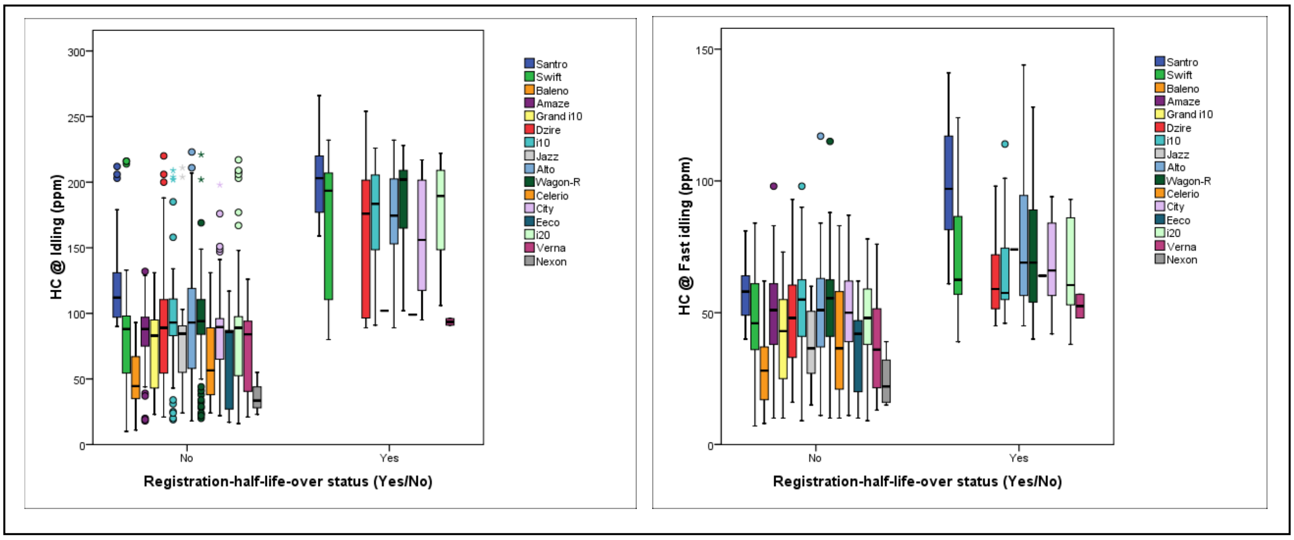


Fig. 4.46 Vehicle regn. life vs. HC emission for top 16 models (at idling and fast idling)

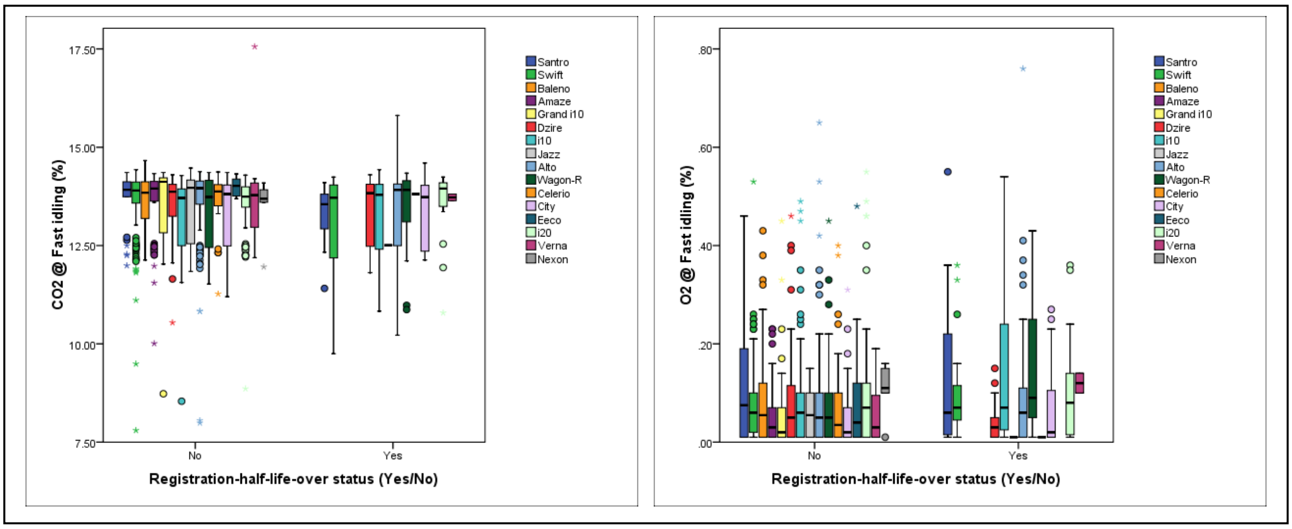


Fig. 4.47 Vehicle regn. life vs. CO_2 and O_2 emission for top 16 models (at fast idling)

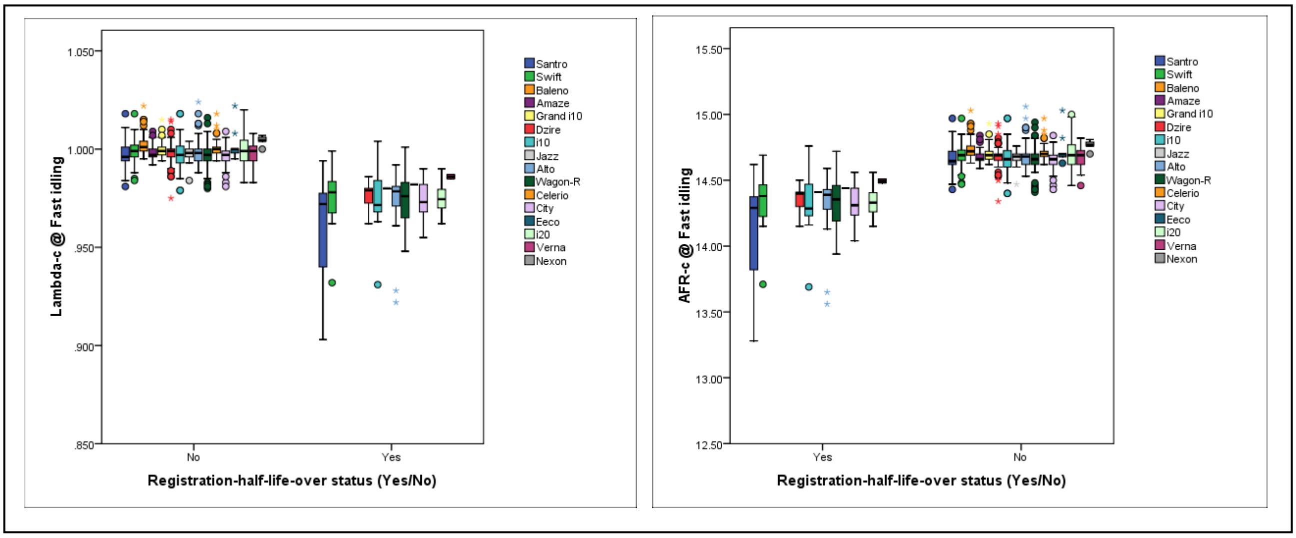


Fig. 4.48 Vehicle regn. life vs. λ and AFR for top 16 models (at fast idling)

4.1.1.5 Vehicle kerb weight

Kerb (curb) weight of a vehicle in-general, refers to unladen weight without any passenger or cargo in it. Kerb weight has only standard accessories as per manufacturer's recommendations and usually the assigned weight while the vehicle is put in under idling condition on a flat surface. The present study investigated the effect of vehicle's kerb weight on tailpipe parameters, such as CO, HC, CO_2, O_2, λ and AFR in idling / fast idling test modes. Scatter plots were drawn to find correlations amongst these variables, if any. The plots are presented dataset-wise (Figures 4.49 – 4.52 for the whole dataset; Figures 4.53 – 4.56 for the top 3 makes and Figures 4.57 – 4.60 for the top 16 models). It was revealed that kerb weight does not seem to influence the tested tailpipe parameters in the two testing modes. The correlation values observed using 2nd polynomial / quadratic trendline equation were too low to draw any reliable conclusion for any of the datasets.

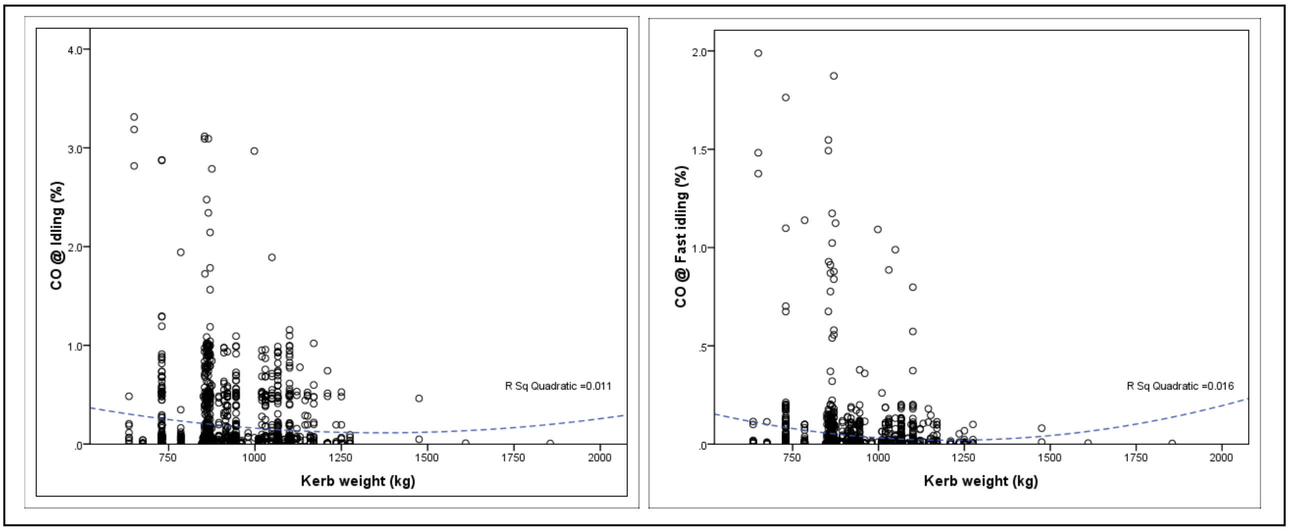


Fig. 4.49 Vehicle kerb weight vs. CO emission (at idling and fast idling)

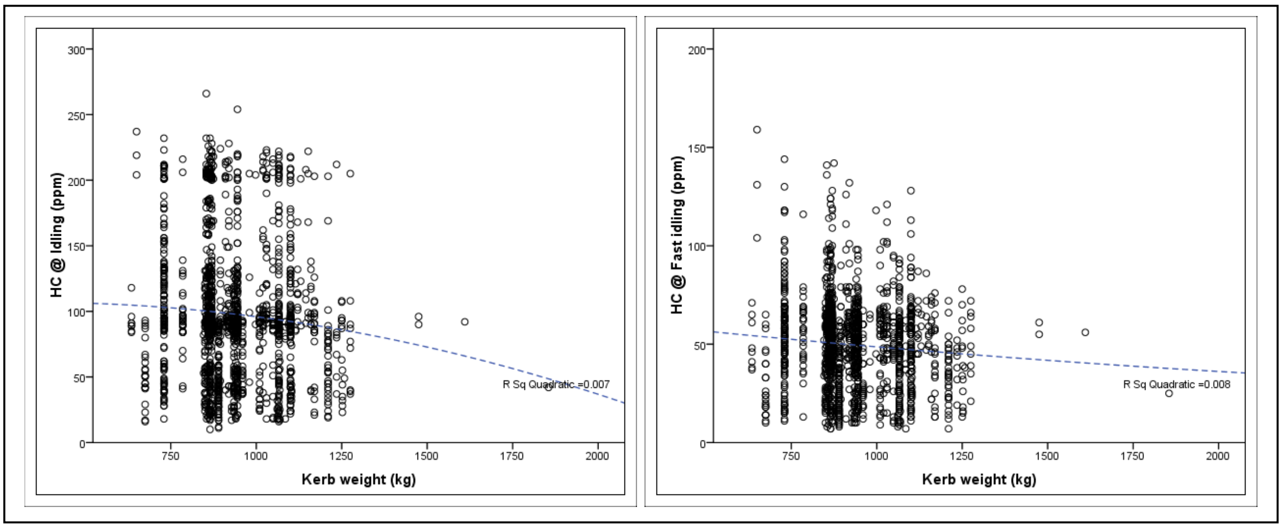


Fig. 4.50 Vehicle kerb weight vs. HC emission (at idling and fast idling)

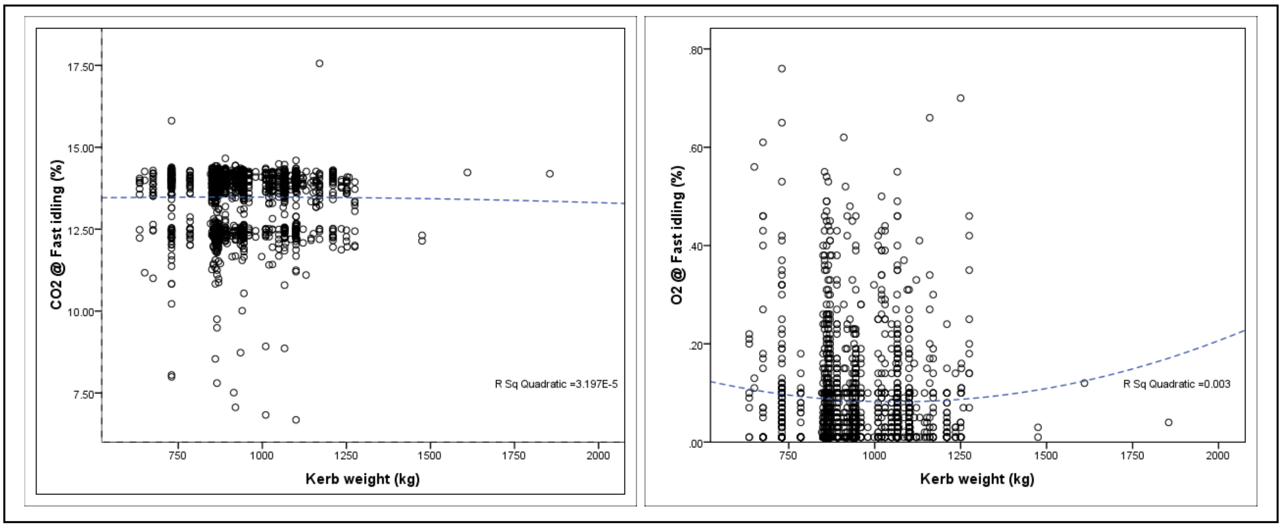


Fig. 4.51 Vehicle kerb weight vs. CO_2 and O_2 emissions (at fast idling)

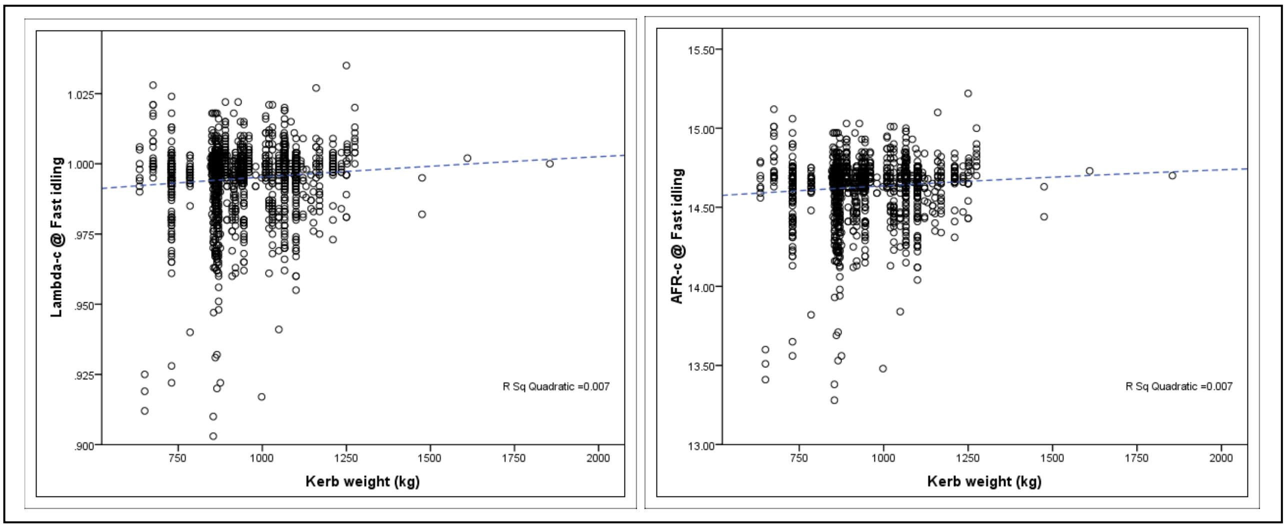


Fig. 4.52 Vehicle kerb weight vs. λ and AFR (at fast idling)

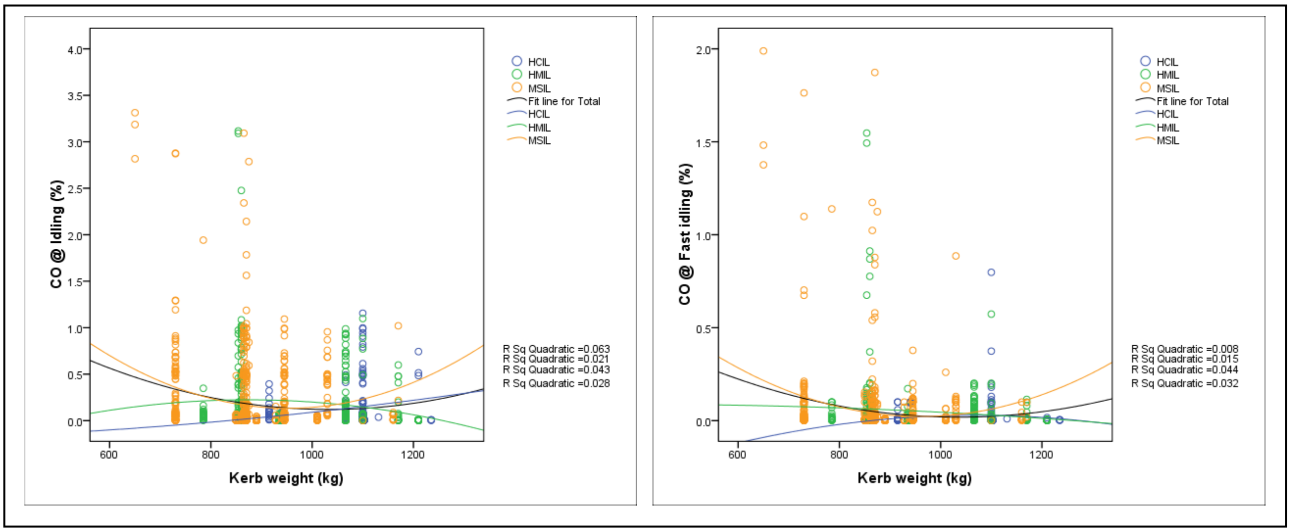


Fig. 4.53 Vehicle kerb weight vs. CO emission for top 3 makes (at idling and fast idling)

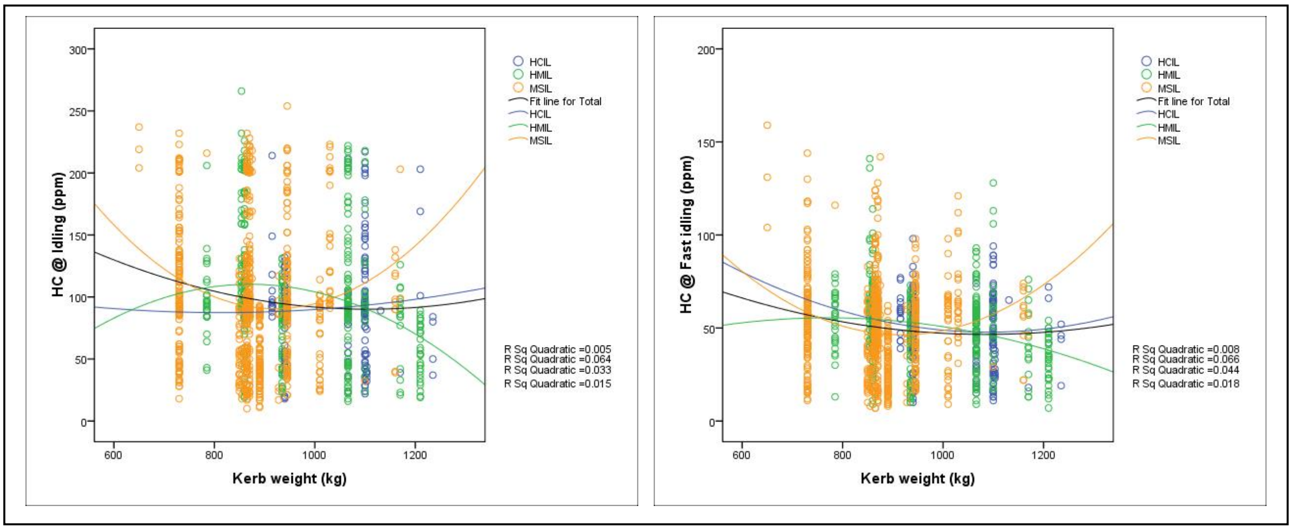


Fig. 4.54 Vehicle kerb weight vs. HC emission for top 3 makes (at idling and fast idling)

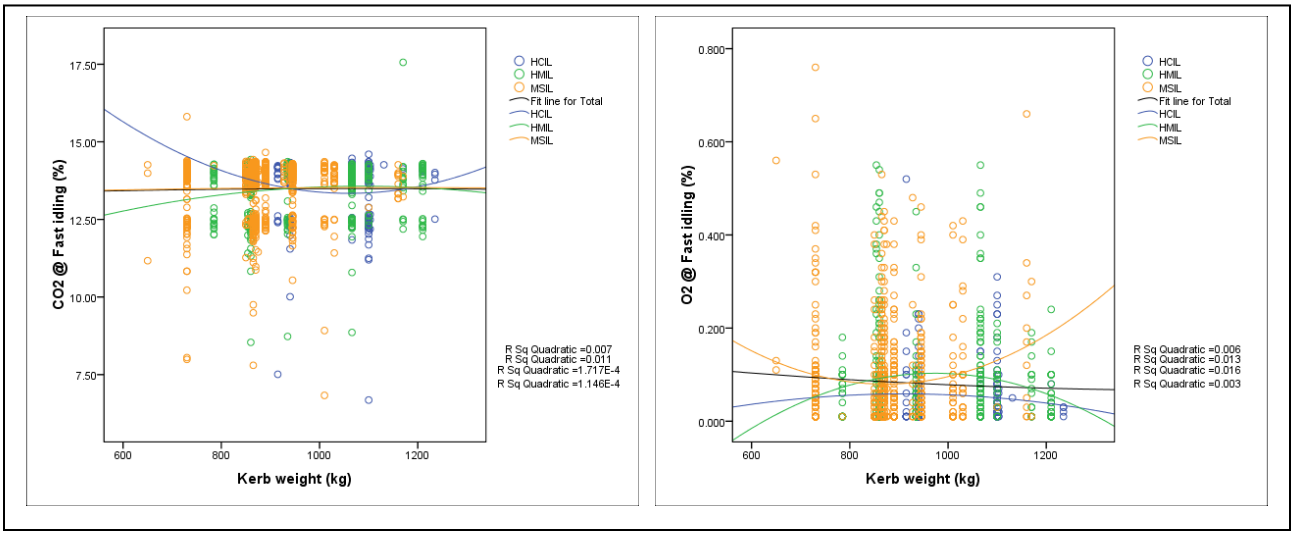


Fig. 4.55 Vehicle kerb weight vs. CO$_2$ and O$_2$ emission for top 3 makes (at fast idling)

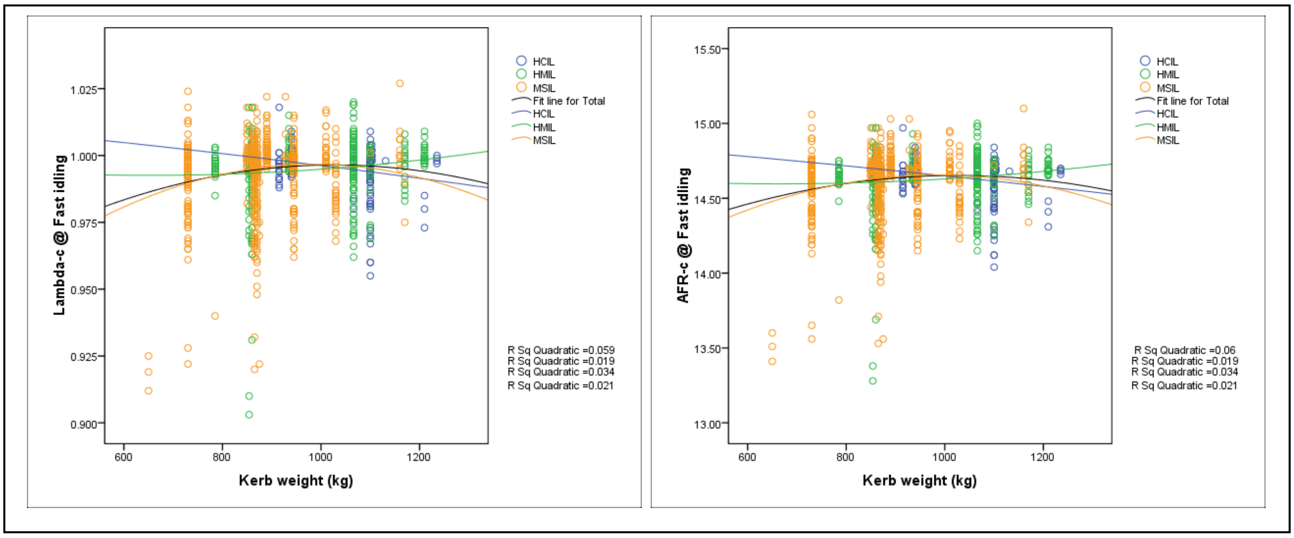


Fig. 4.56 Vehicle kerb weight vs. λ and AFR for top 3 makes (at fast idling)

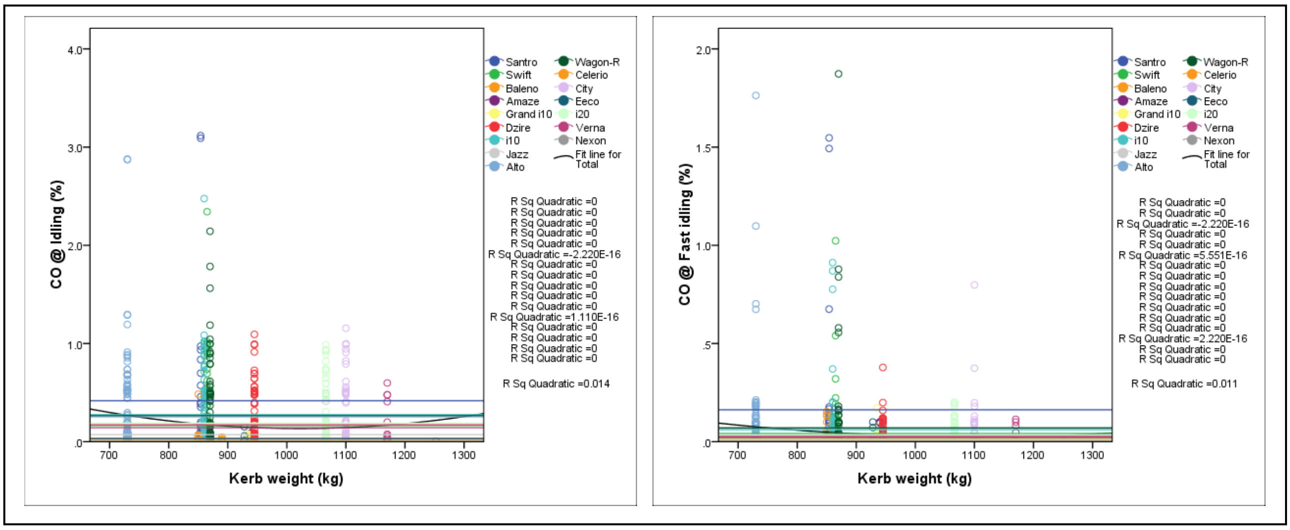


Fig. 4.57 Vehicle kerb eight vs. CO emission for top 16 models (at idling and fast idling)

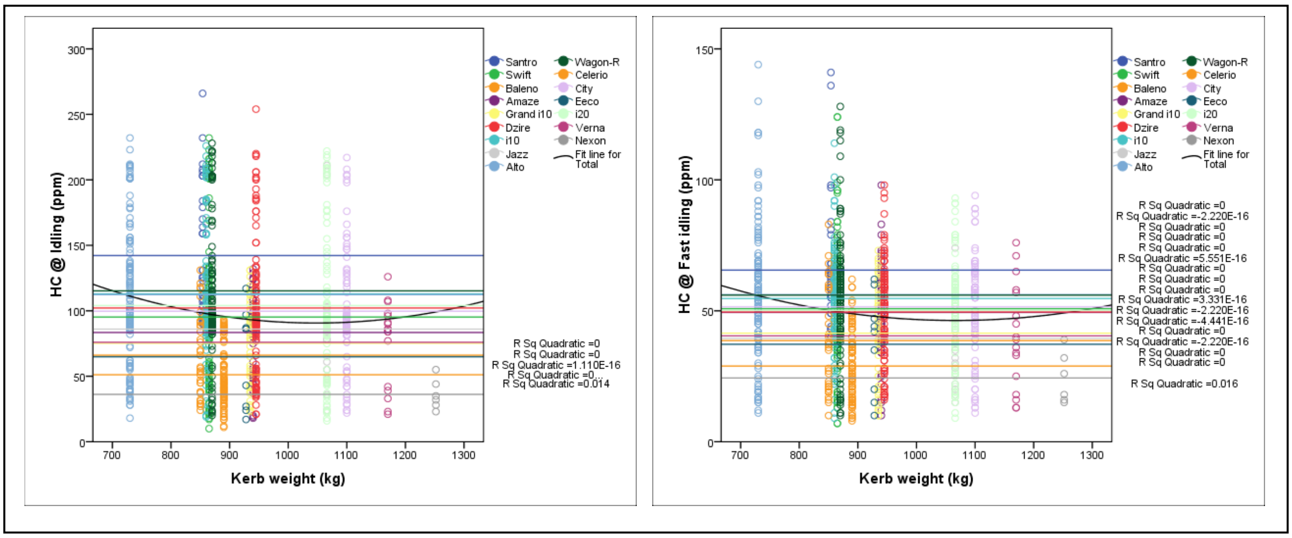


Fig. 4.58 Vehicle kerb eight vs. HC emission for top 16 models (at idling and fast idling)

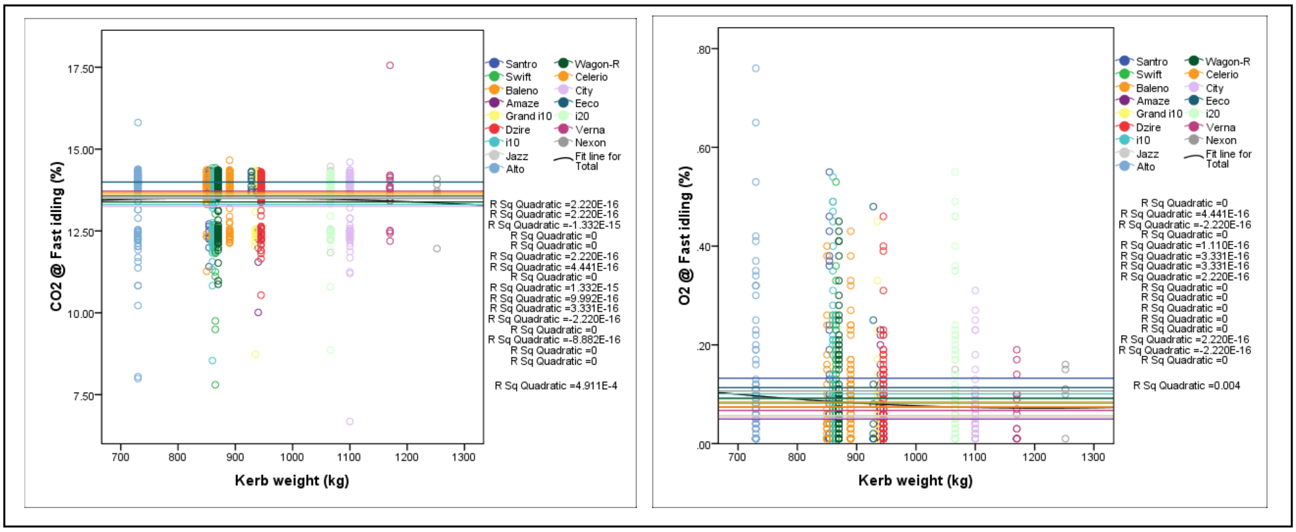


Fig. 4.59 Vehicle kerb weight vs. CO_2 and O_2 emission for top 16 models (at fast idling)

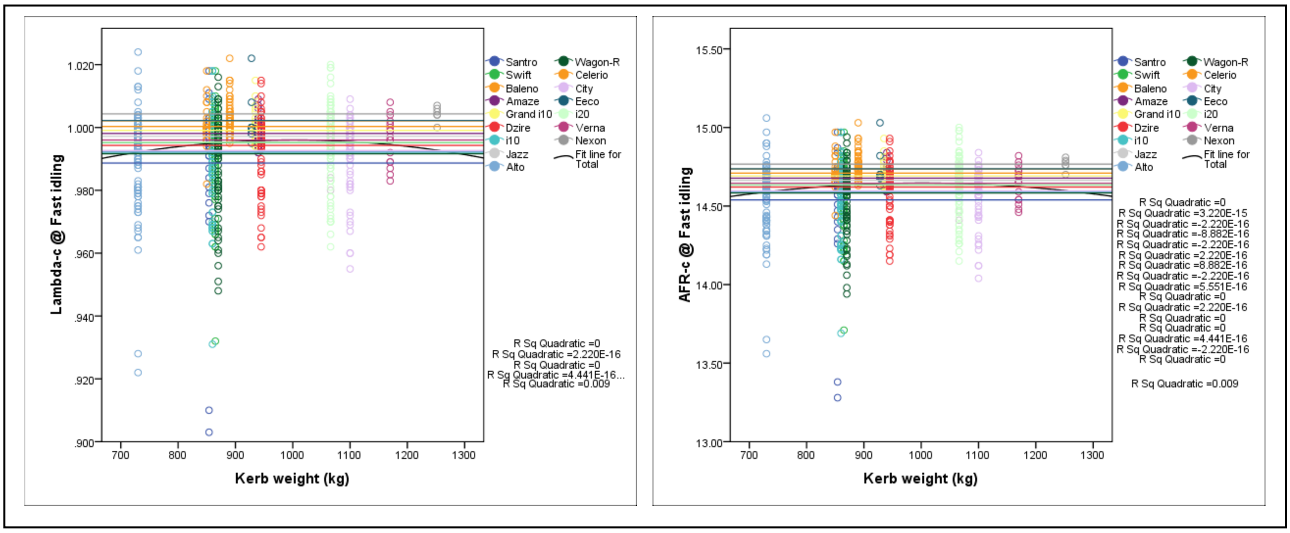


Fig. 4.60 Vehicle kerb weight vs. λ and AFR for top 16 models (at fast idling)

4.1.1.6 Vehicle transmission type

Two vehicle transmission types were tested in the present emission testing program, namely, manual and automatic in a bid to ascertain if the transmission system had any impact on tailpipe parameters studied. It is revealed that the vehicle transmission type has some effect on tailpipe CO and HC. It was found that vehicles with automatic transmission have a lower range of both CO and HC emission compared to those with manual transmission (Figs. 4.61 – 4.62). It may also be noted that this reduction is present in both testing cases, although not to a very significant level. Further, the transmission system does not seem to be correlated with the tailpipe emission and / or other parameters as the there was no variation noted in the case of CO_2, O_2, λ and AFR in fast idling mode (Figs. 4.63 – 4.64).

In vehicle make terms, it was observed that MSIL make had maximum variation in CO and HC values in either testing modes followed by HCIL make. The performance of HMIL make could not be compared due to the unavailability of any automatic model for this make (Figs. 4.65 – 4.68). It was also found that owing to a very lesser number of automatic cars in the total number of cars represented by the top 16 models, the model-wise comparison of transmission type vs. tailpipe parameters could not bring about any solid argument (Figs. 4.69 – 4.72).

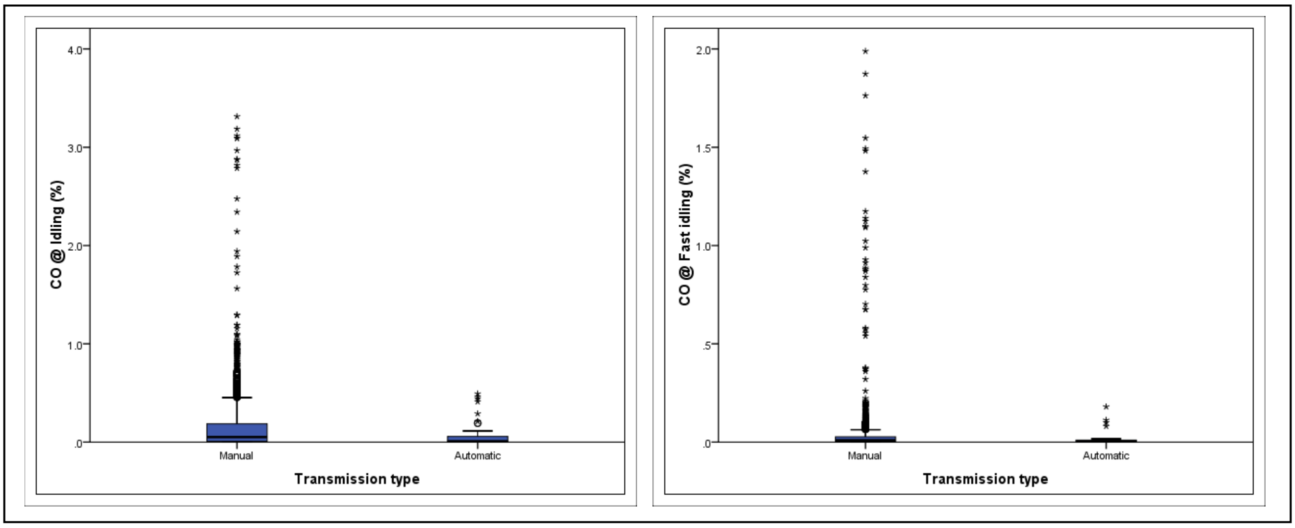


Fig. 4.61 Vehicle transmission vs. CO emission (at idling and fast idling)

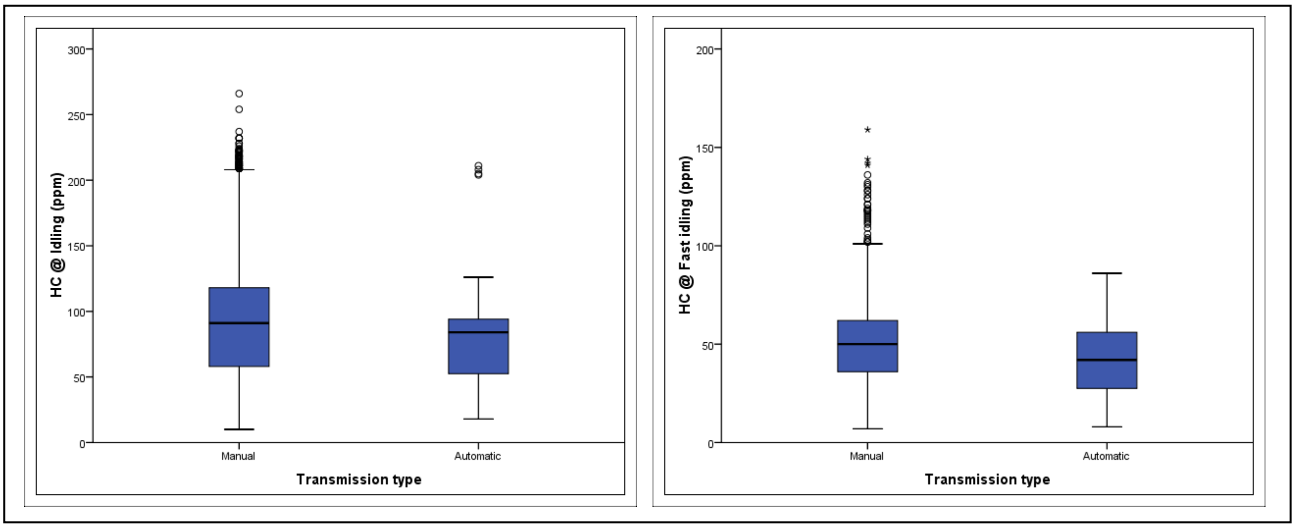


Fig. 4.62 Vehicle transmission vs. HC emission (at idling and fast idling)

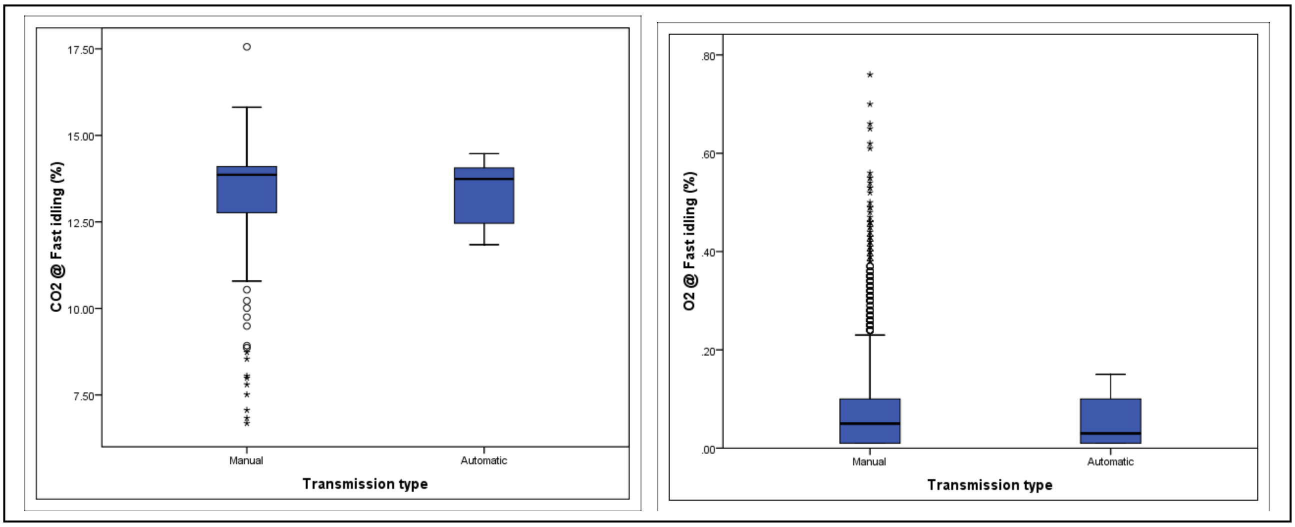


Fig. 4.63 Vehicle transmission vs. CO_2 and O_2 emissions (at fast idling)

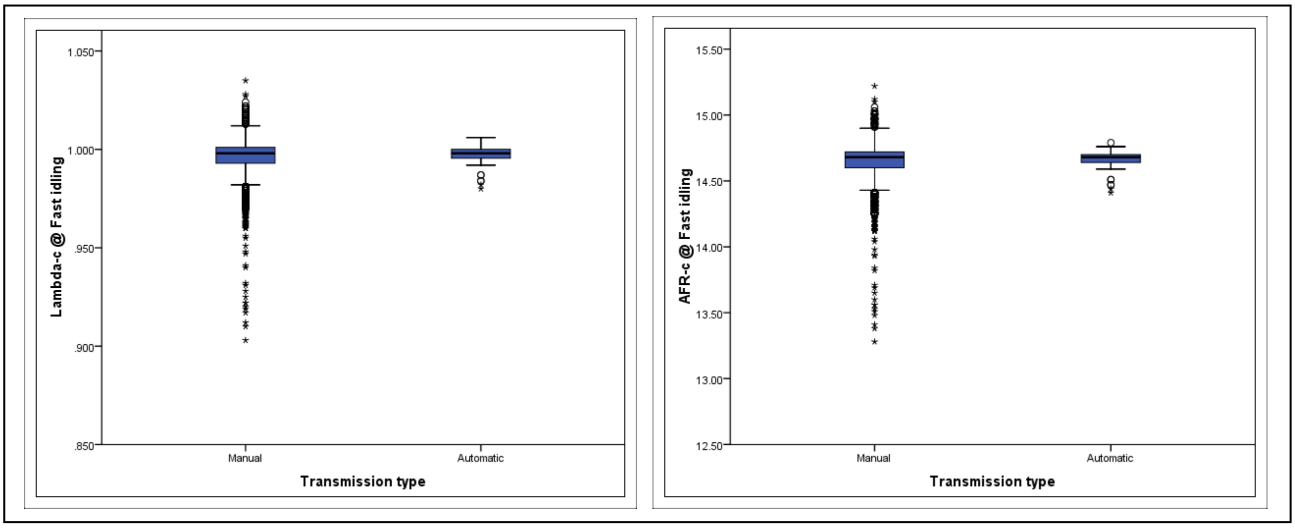


Fig. 4.64 Vehicle transmission vs. λ and AFR (at fast idling)

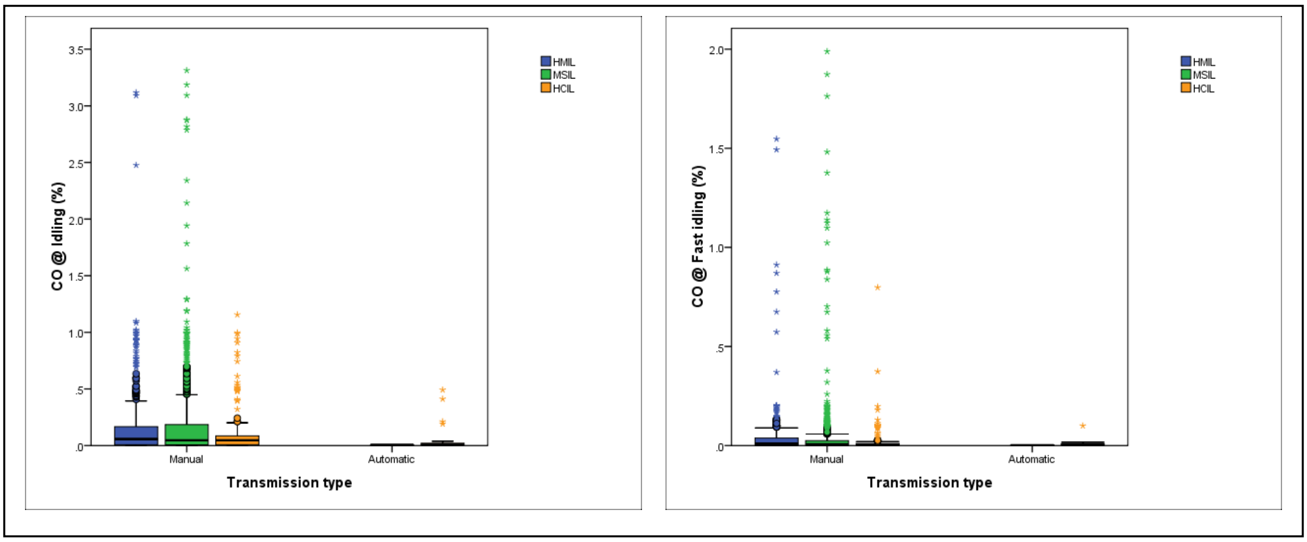


Fig. 4.65 Vehicle transmission vs. CO emission for top 3 makes (at idling and fast idling)

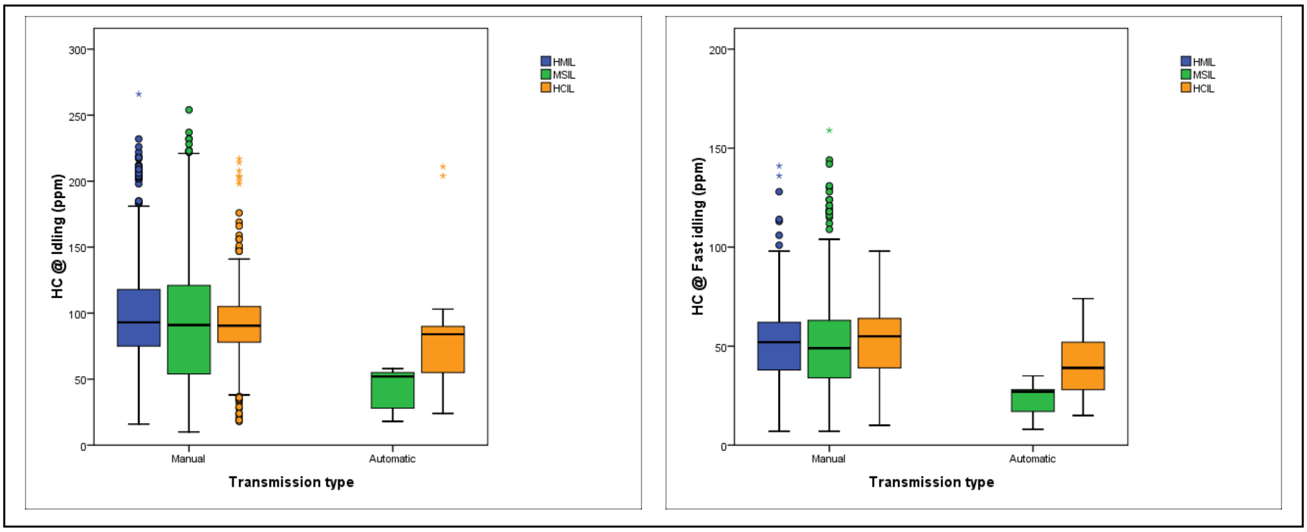


Fig. 4.66 Vehicle transmission vs. HC emission for top 3 makes (at idling and fast idling)

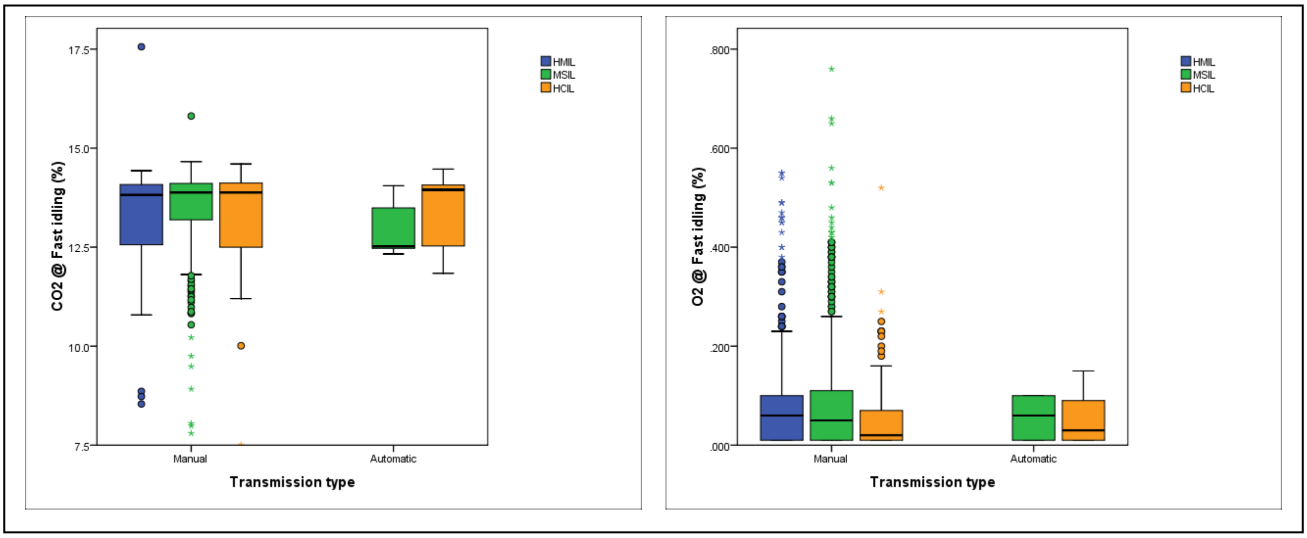


Fig. 4.67 Vehicle transmission vs. CO_2 and O_2 emission for top 3 makes (at fast idling)

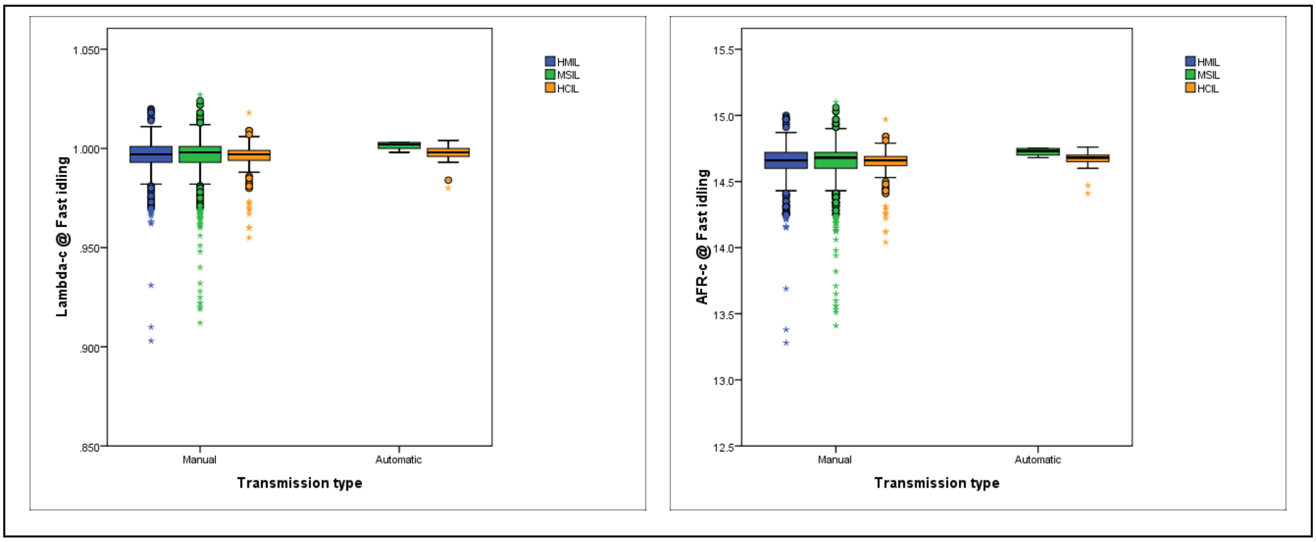


Fig. 4.68 Vehicle transmission vs. λ and AFR for top 3 makes (at fast idling)

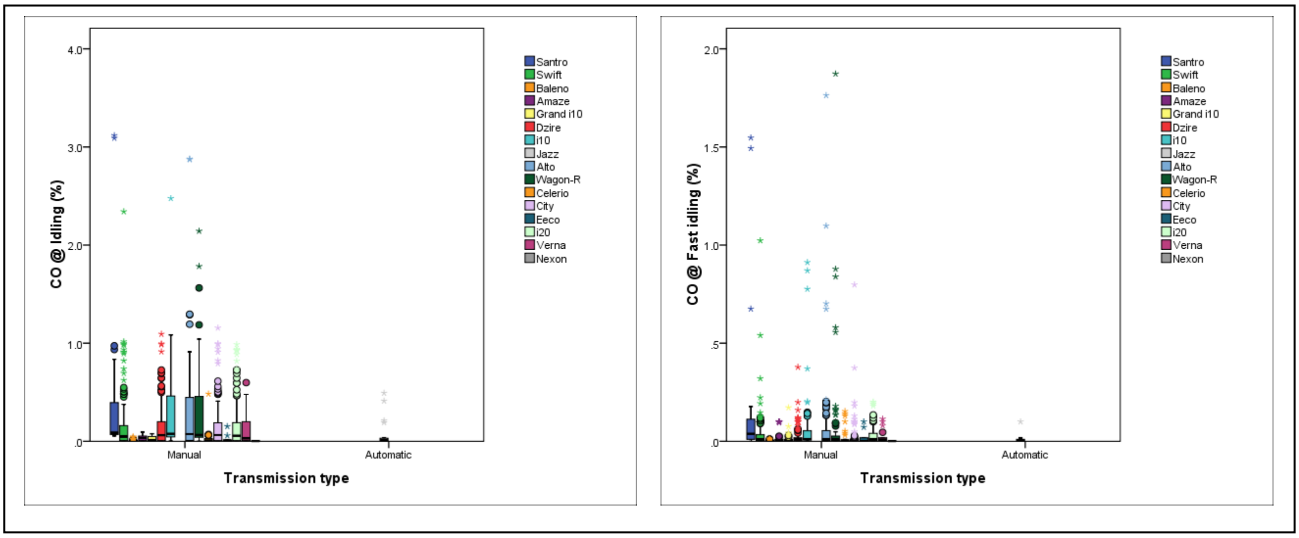


Fig. 4.69 Vehicle transmission vs. CO emission - top 16 models (at idling and fast idling)

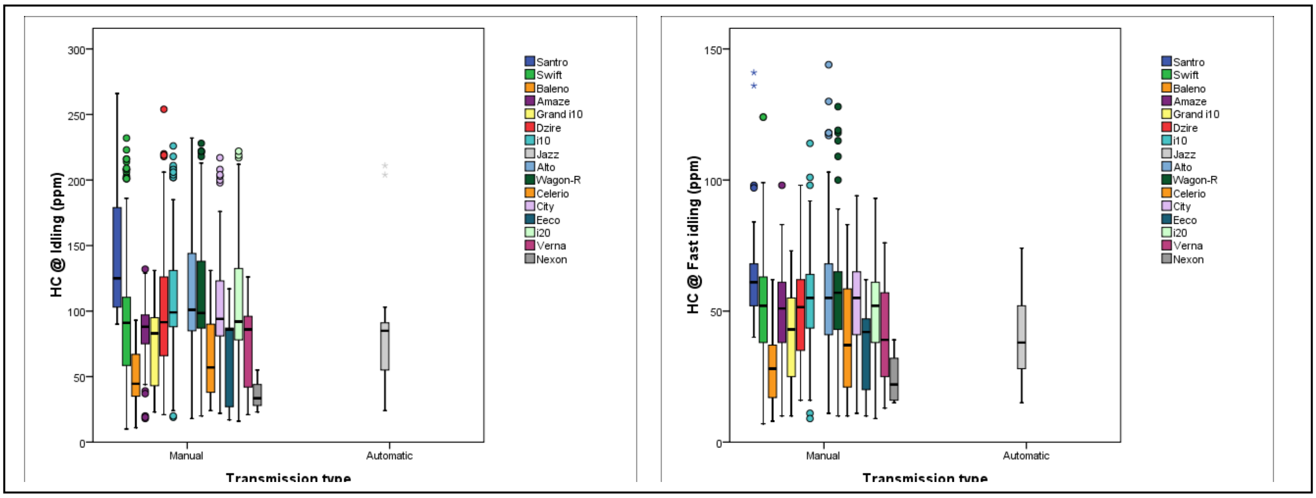


Fig. 4.70 Vehicle transmission vs. HC emission - top 16 models (at idling and fast idling)

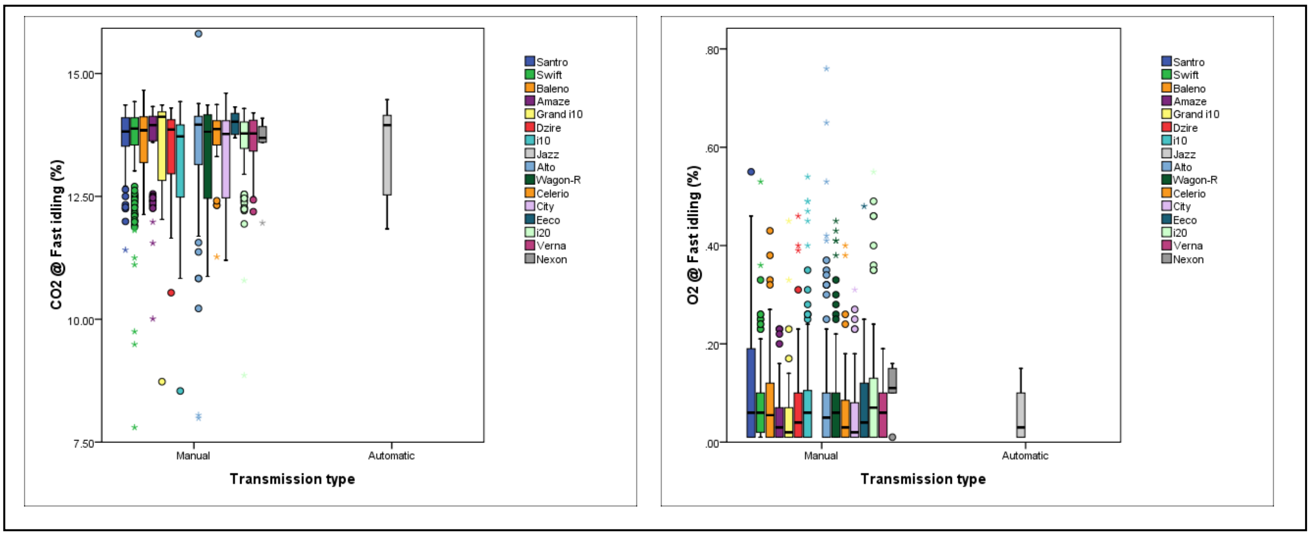


Fig. 4.71 Vehicle transmission vs. CO_2 and O_2 emission - top 16 models (at fast idling)

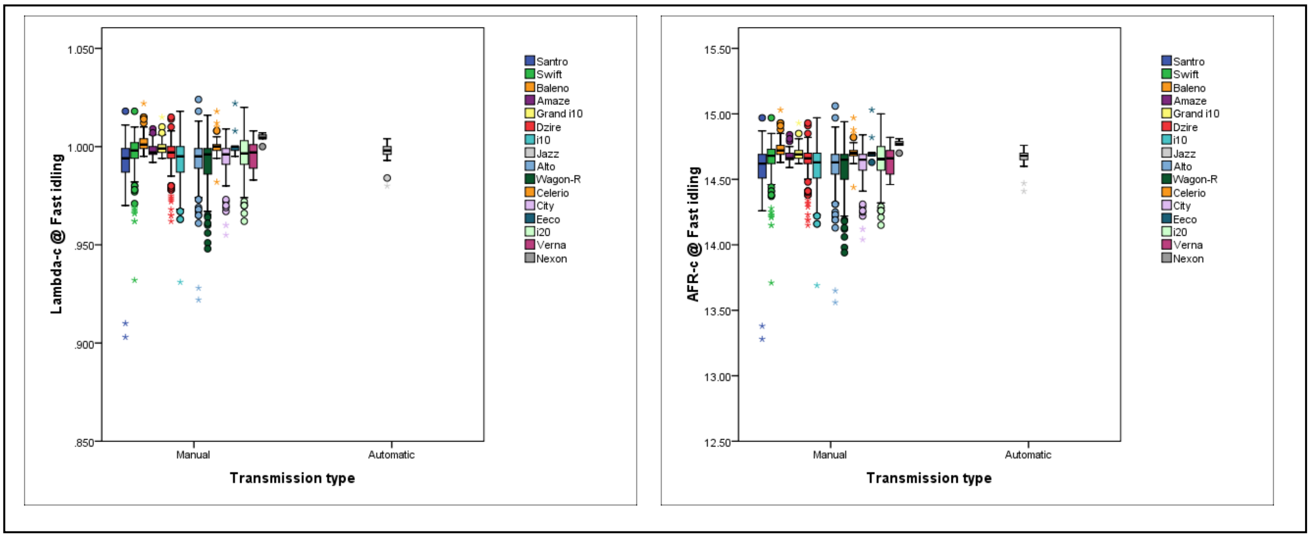


Fig. 4.72 Vehicle transmission vs. λ and AFR - top 16 models (at fast idling)

4.1.1.7 Vehicle drivetrain type

The study also focused on finding out if there was any effect of vehicle’s drivetrain type on tailpipe emission / parameters. Three drivetrains were encountered in the present work, namely, front (FWD – Front Wheel Drive, i.e., only front tyres receive power from engine); rear (RWD – Rear Wheel Drive, i.e., only rear tyres receive power from engine) and 4*4 (AWD – All-Wheel Drive, i.e., all four wheels receive power from the engine simultaneously). It was found that vehicles with RWD emit relatively lesser amount of CO in idling test conditions compared to FWD and AWD while AWD had the highest range of CO emission in the given test condition, even though FWD had the maximum number of outliers in the data points. This observation was different in the case of fast idling CO values with RWD having maximum range followed by FWD and AWD (Fig. 4.73).

HC emission in both testing mode, however, was not as conclusive as in the case of CO with HC not varying much with drivetrain type. Although RWD seemed to have emitted the lowest values in idle testing in a range that is hardly different from AWD and FWD, the difference was found to be rather indifferent in the case of fast idling mode (Fig. 4.74). Range-wise speaking, RWD depicted lowest CO_2, yet highest O_2 closely followed by FWD and AWD (Fig. 4.75). Similarly, λ and AFR were found to be very near to ideal (stoichiometric) levels in RWD compared to FWD and AWD drivetrains (Fig. 4.76).

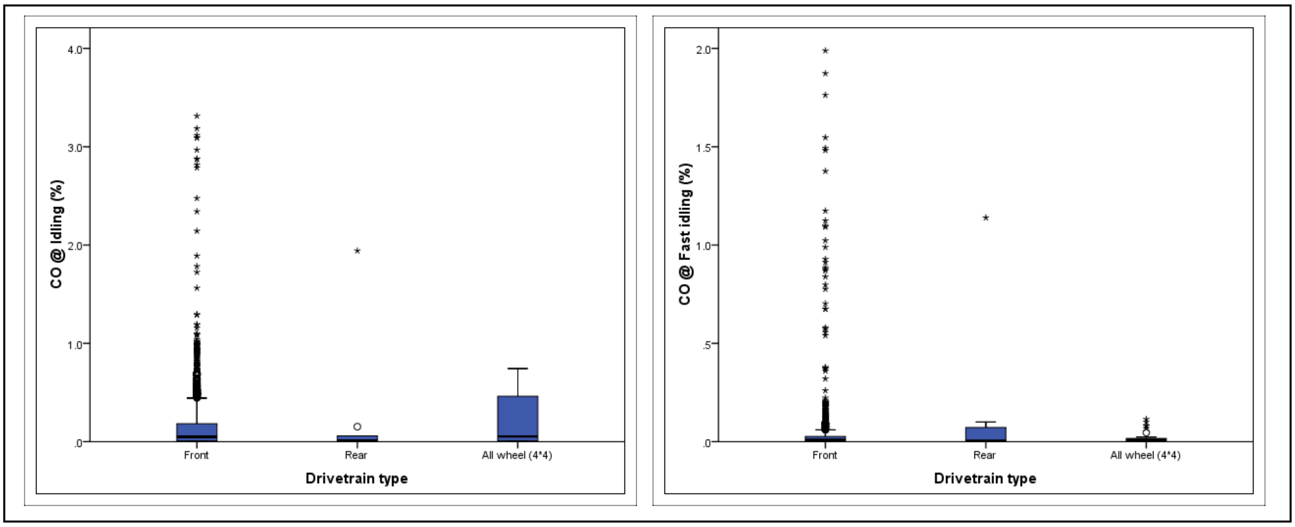


Fig. 4.73 Vehicle drivetrain vs. CO emission (at idling and fast idling)

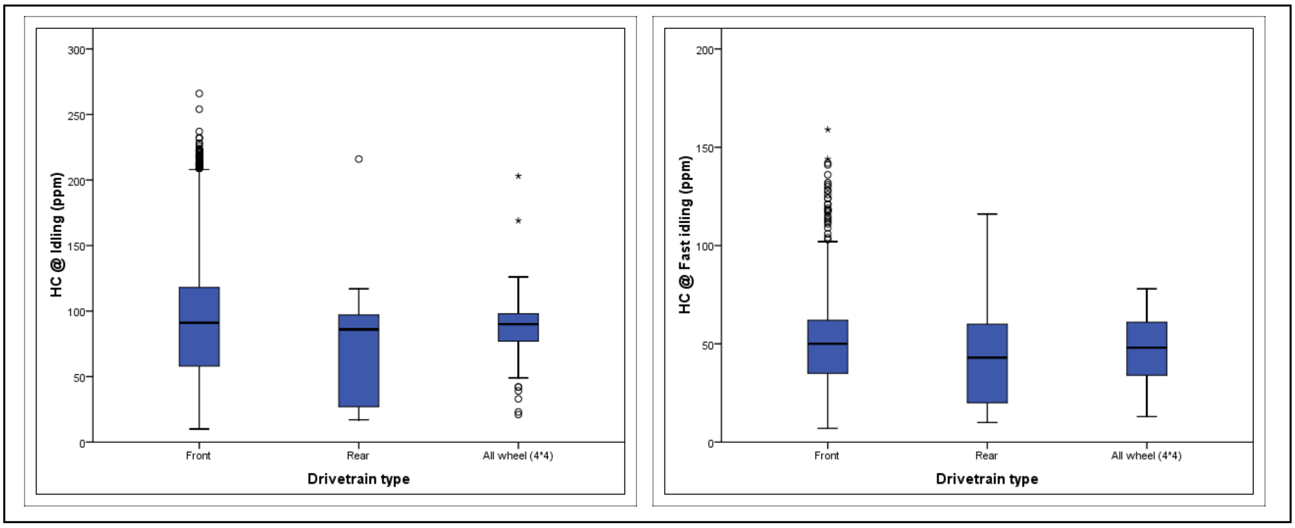


Fig. 4.74 Vehicle drivetrain vs. HC emission (at idling and fast idling)

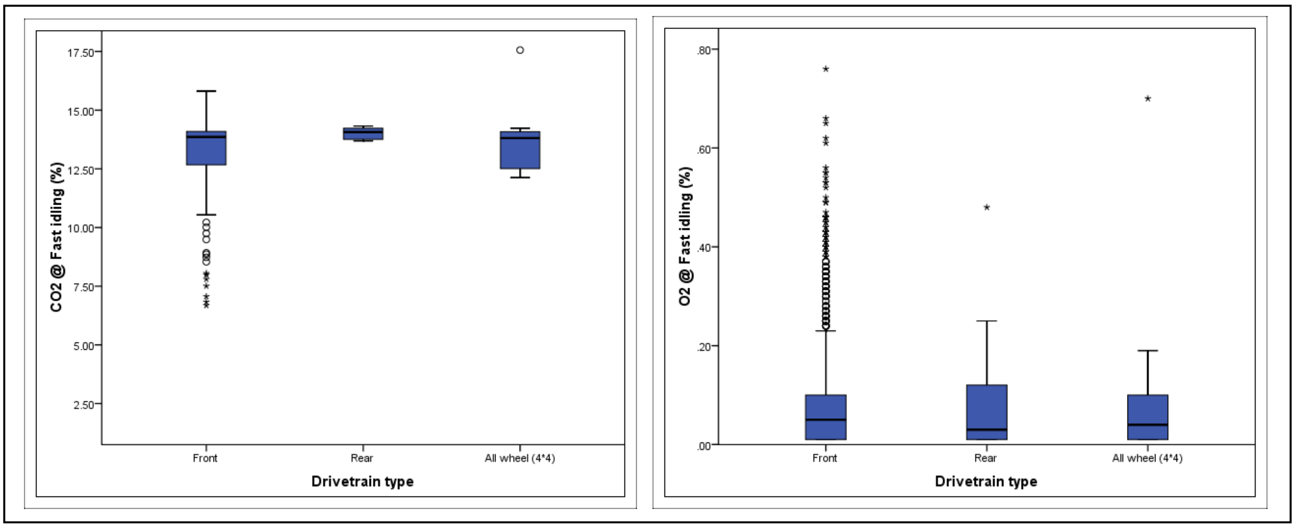


Fig. 4.75 Vehicle drivetrain vs. CO_2 and O_2 emissions (at fast idling)

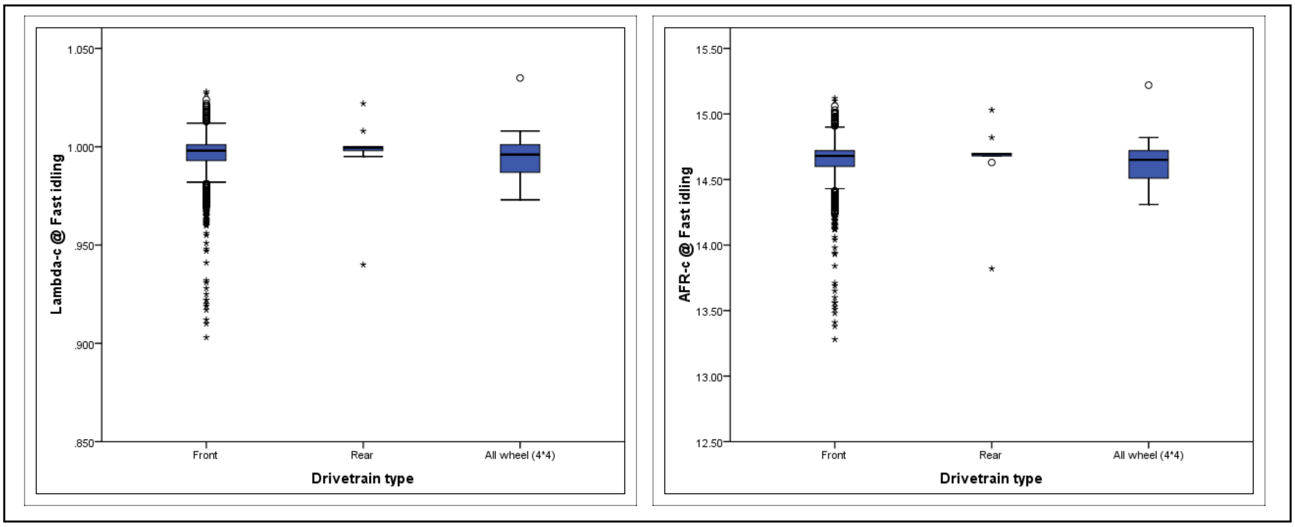


Fig. 4.76 Vehicle drivetrain vs. λ and AFR (at fast idling)

Make-wise scenario was found to be in sync with that reflected in the whole dataset analysis; however, certain notes may be made. For e.g., only MSIL make had a representation of RWD; MSIL has no vehicle in AWD category as this category belonged only to certain high-end SUV makes (which represent a very small number in the entre dataset); AWDs have the highest range of HC emission in idle testing mode (HCIL make) followed by the other two (MSIL and HMIL makes); RWDs' range of HC emission does not change in fast idling condition. Further, CO_2 and O_2 emission ranges are almost the same for all makes. Similarly, λ and AFR also follow the same pattern as of CO_2 and O_2 (Figs. 4.77 – 4.80).

Santro, i10, i20 and Wagon-R (all FWDs) demonstrated the highest level of CO emission in both idle and fast idling testing modes. Alto. City, Dzire and Swift (FWDs) get added up while considering variation in HC emissions in both test modes. Verna (AWD) had the lowest emission for CO in either testing modes but depicted relatively higher levels of HC emissions. Eeco with RWD drivetrain performed better compared to Verna in CO emission but was at par in the case of HC (considering idle testing modes). CO_2 and O_2 were depicted for maximum range in the case of FWD vehicles with the highest number of outliers, followed by AWD and RWD, whereas emission range-wise, λ and AFR were found to be highest in FWD vehicles, closely followed by AWD and RWD (Figs. 4.81 – 4.84). In view of the number of vehicles with RWD being very small, far lesser than even AWDs, there exists a scope for bettering the corresponding findings with a larger model-wise data set.

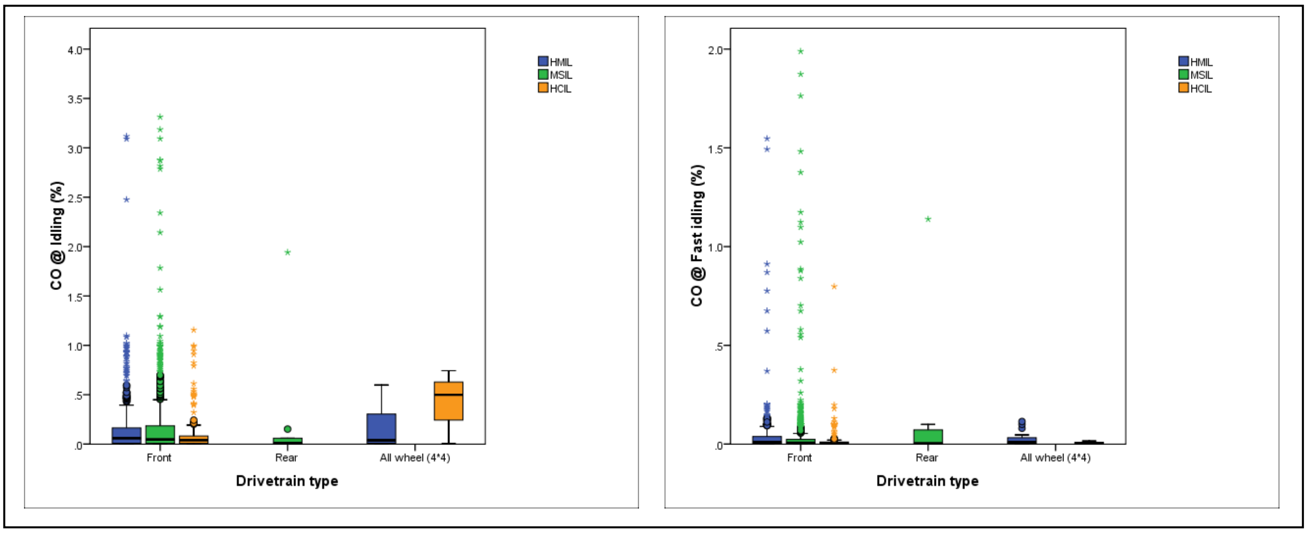


Fig. 4.77 Vehicle drivetrain vs. CO emission for top 3 makes (at idling and fast idling)

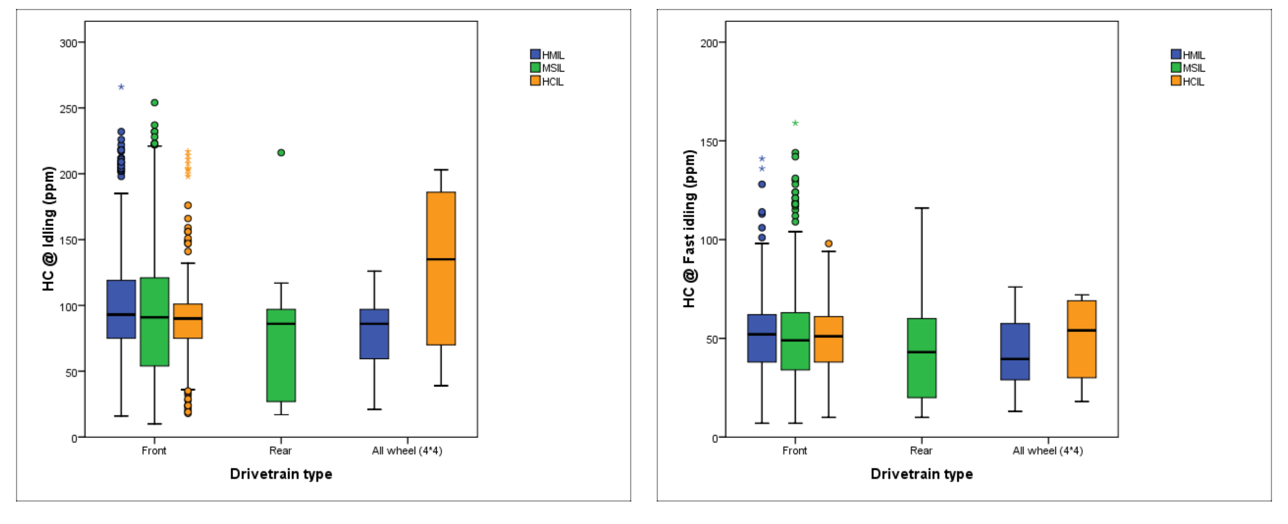


Fig. 4.78 Vehicle drivetrain vs. HC emission for top 3 makes (at idling and fast idling)

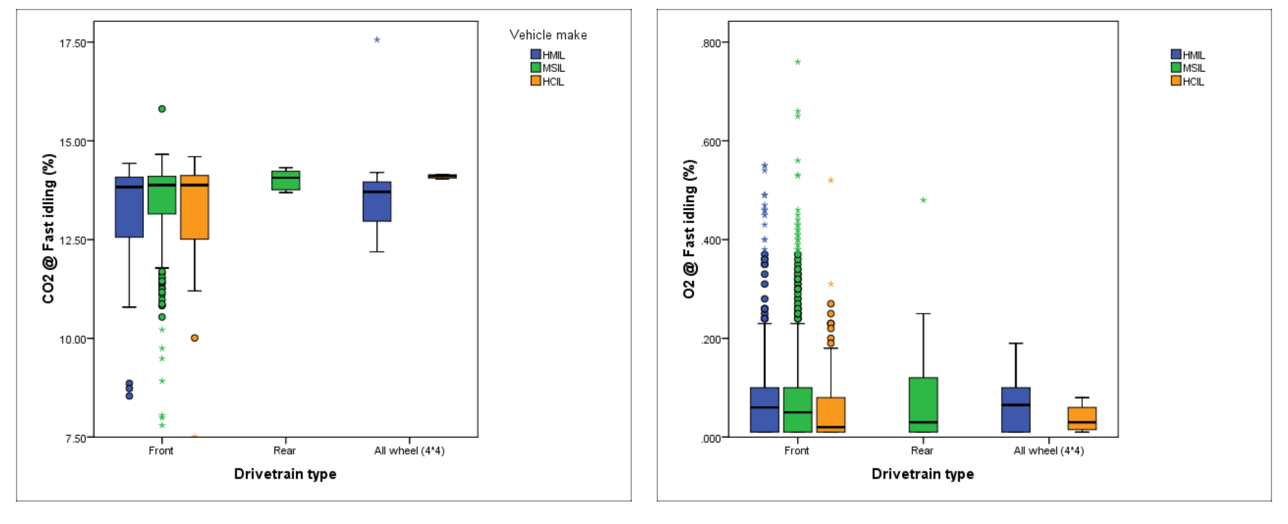


Fig. 4.79 Vehicle drivetrain vs. CO_2 and O_2 emission for top 3 makes (at fast idling)

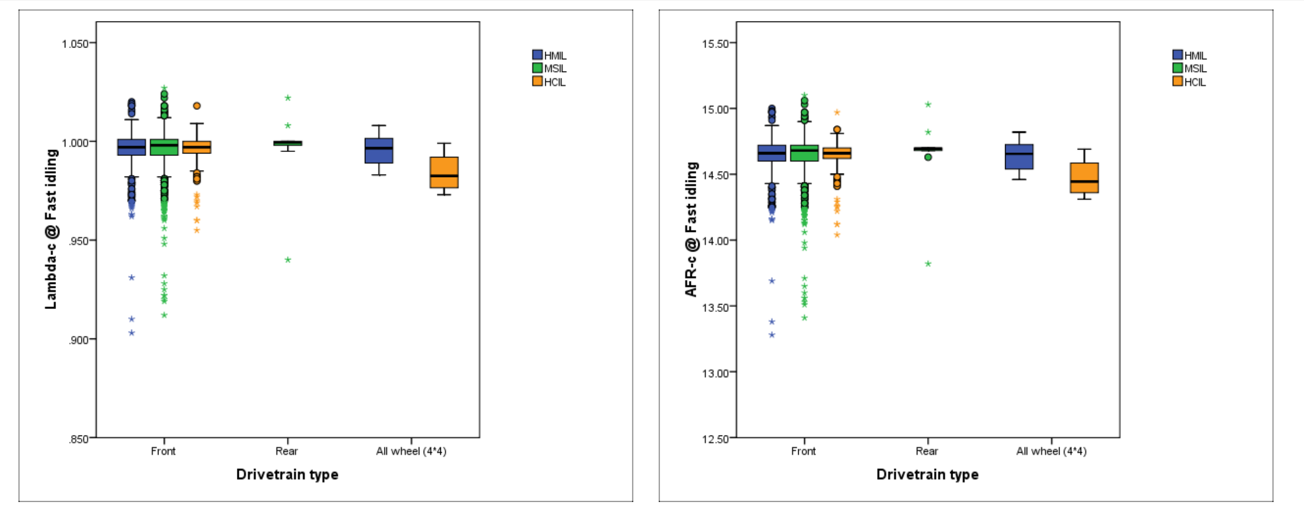


Fig. 4.80 Vehicle drivetrain vs. λ and AFR for top 3 makes (at fast idling)

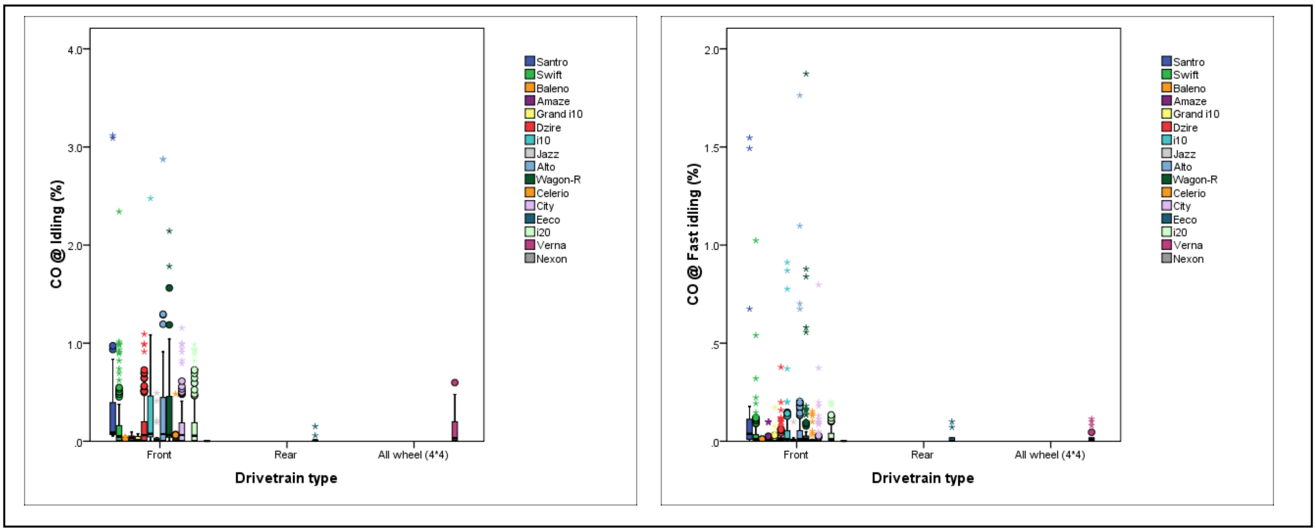


Fig. 4.81 Vehicle drivetrain vs. CO emission - top 16 models (at idling and fast idling)

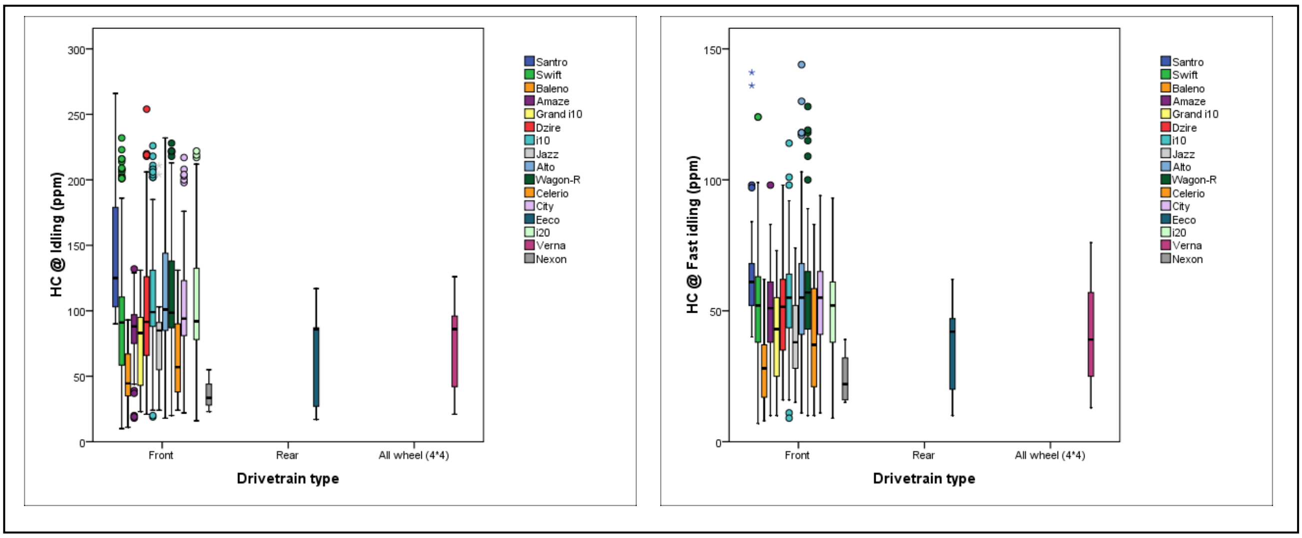


Fig. 4.82 Vehicle drivetrain vs. HC emission - top 16 models (at idling and fast idling)

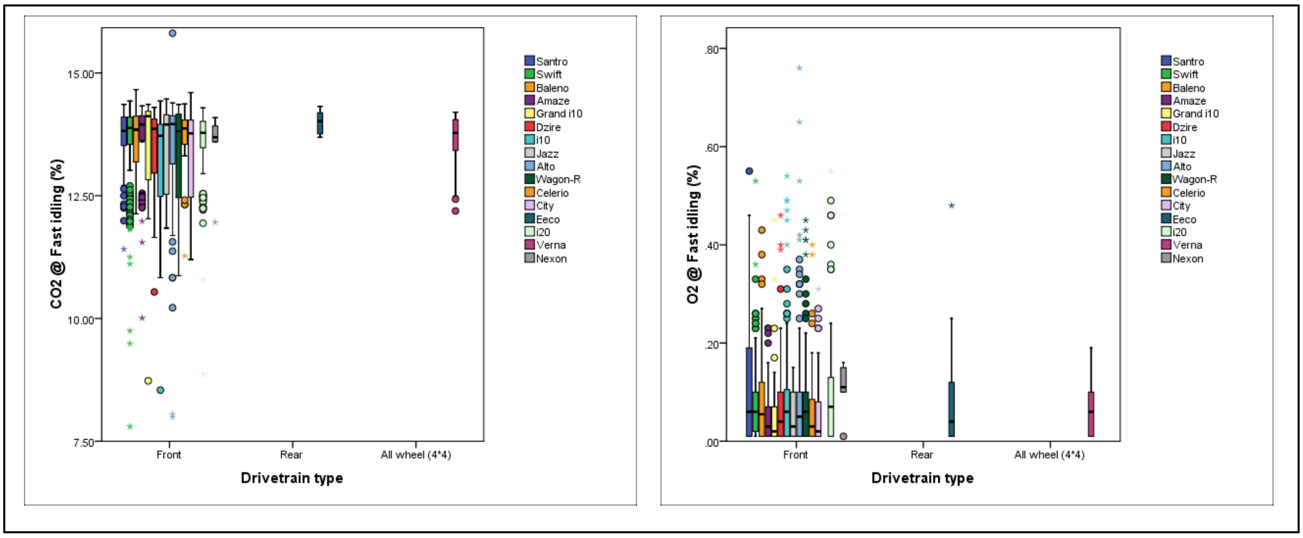


Fig. 4.83 Vehicle drivetrain vs. CO_2 and O_2 emission - top 16 models (at fast idling)

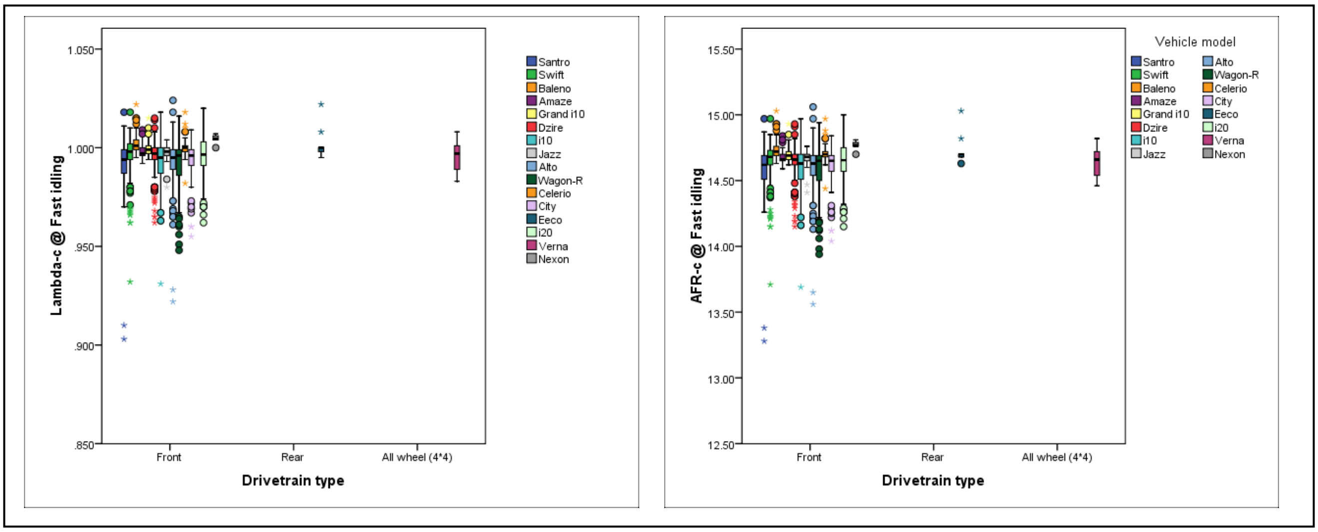


Fig. 4.84 Vehicle drivetrain vs. λ and AFR - top 16 models (at fast idling)

4.1.1.8 Vehicle emission norm (at manufacturing)

The exhaust emission norms are progressively becoming more and more stringent worldwide with a primary aim of inducing the production of vehicles having better performance towards compliance to emission norms thereby achieving a reduction in the automobile-generated air pollution. In this connection, the current study investigated the effect of concurrent emission norms on the tailpipe emission and other related parameters. Although the vehicles were tested for their compliance to in-use emission norms in light of the existing PUC certification system in India, the data analysis was done based on the emission norm the vehicle supposedly complied with, while registered and put into operation. The emission norms analyzed were BS (Bharat Stage) norms (such as BS 2000, BS II, BS III and BS IV) in India which were adopted on the lines of Euro norms' progression.

The study reported a strong influence of progressive emission norms (say newer norms) on tailpipe emission and other tested parameters. For the whole dataset, the CO, HC (under both idle and fast idle testing conditions) and O_2 emissions (under fast idling conditions) were found to improve for relatively newer norms. The range of emission of these parameters was found to decrease with the introduction of stringent norms following the order BS IV > BS III > BS II > BS 2000 (introduced in India in the years 2010, 2005, 2001 and 2000 respectively). Only CO_2 emission was found to be independent of any emission norm and did not fluctuate with onset of any BS norm any significantly. Two other parameters λ and AFR were also reported to be strongly influenced by the emission norms and depicted a reduction in ranges with the application of newer norms in the same manner as in the case of CO, HC and O_2 emissions (Figs. 4.85 – 4.88).

All vehicle makes (HMIL, MSIL and HCIL) also report a huge degree of reduction in CO, HC and O_2 emission levels between vehicles having BS III as complying emission norm compared to those having to comply with BS IV. BS IV has a remarkably lesser range of CO, HC and O_2 emissions and has brought down a significant reduction in CO and HC levels in both test conditions. BS III also presents a reasonable degree of CO and HC emission reduction compared to BS II. It is seen that the MSIL and HMIL makes have the sharpest reduction in the emission levels while HCIL seemed to follow a rather lesser variation. λ and AFR reported the same variation in their reduction vias-a-vis emission norms across all makes (Figs. 4.89 – 4.92). Alto, Swift, i10 and Wagon-R recorded the highest reduction in CO and HC (fast idling) between BS III and BS IV norms while Santro and City reported a sharp reduction in HC (idling) values. Similar was the case with other parameters, e.g., O_2, λ and AFR while CO_2 remains unaffected by emission norms in both make-wise and model-wise scenarios (Figs. 4.93 – 4.96).

As the more stringent emission norms are being adopted worldwide, there may be a scope for analyzing a similar or larger dataset or make or model or fuel-specific emission dataset considering newer norms to ascertain any further reduction in vehicular emission characteristics in the future.

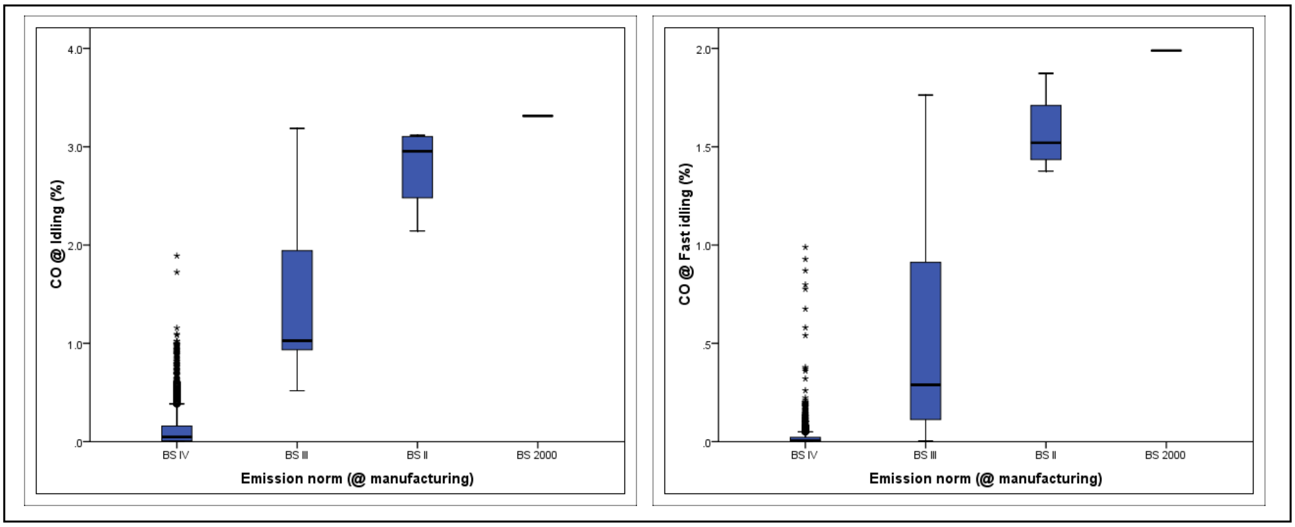


Fig. 4.85 Emission norm vs. CO emission (at idling and fast idling)

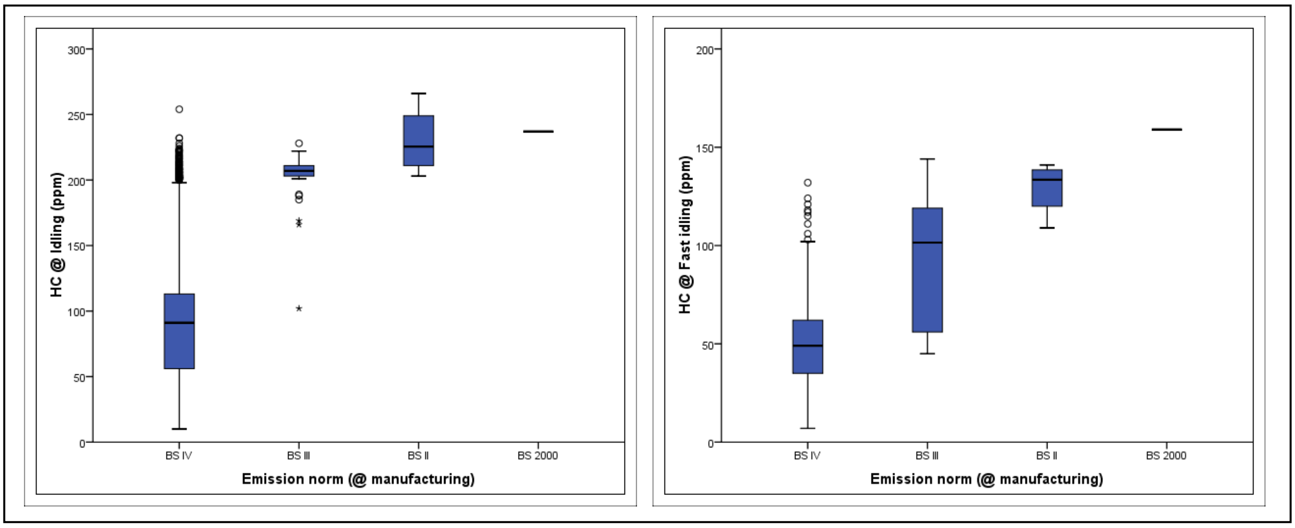


Fig. 4.86 Emission norm vs. HC emission (at idling and fast idling)

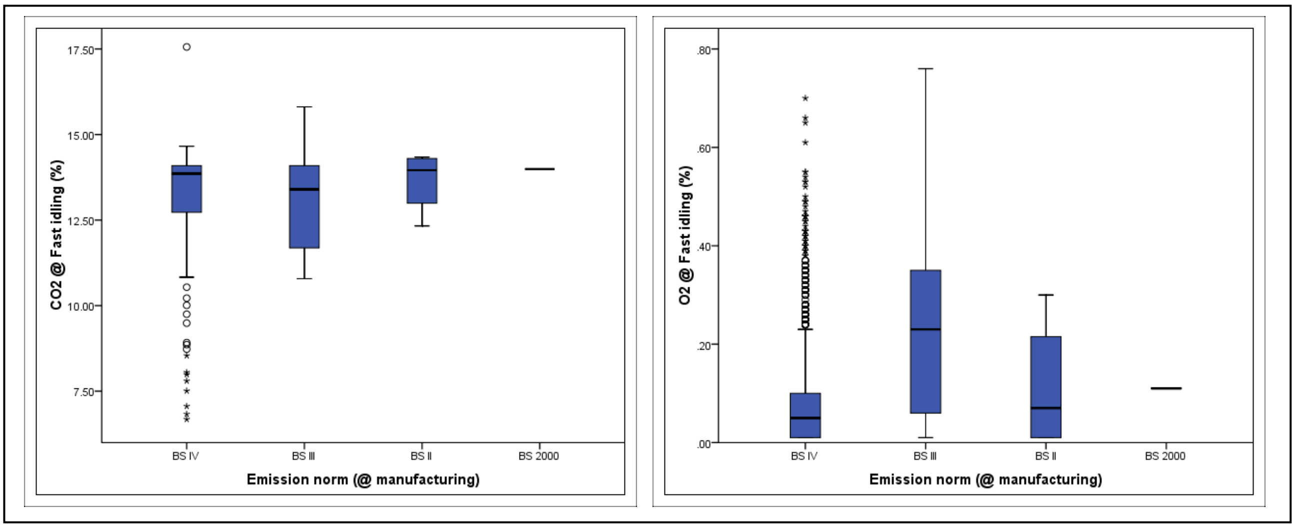


Fig. 4.87 Emission norm vs. CO_2 and O_2 emissions (at fast idling)

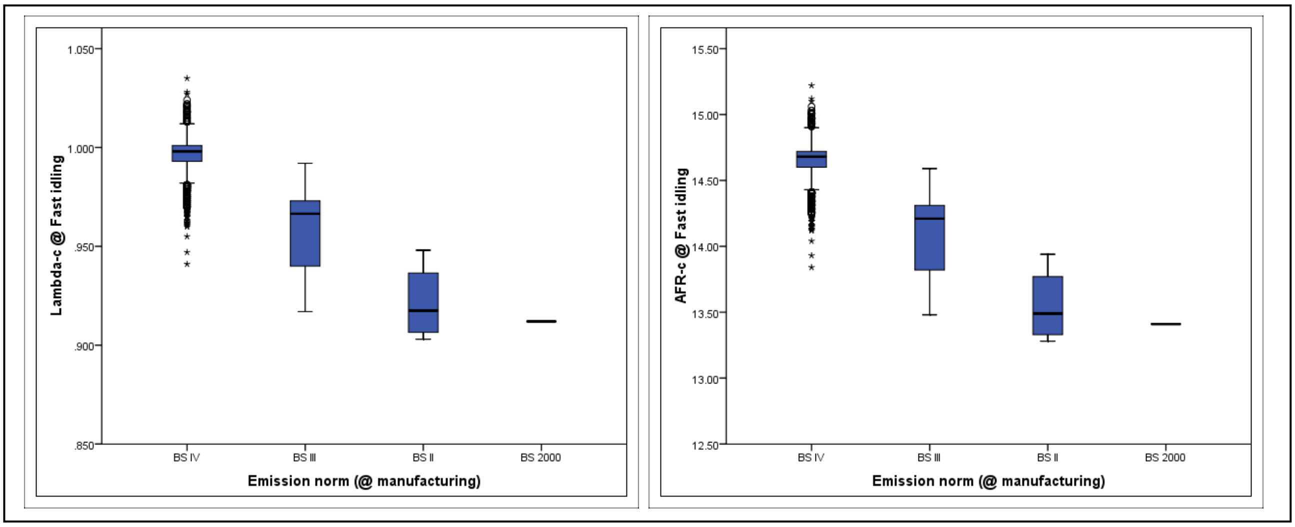


Fig. 4.88 Emission norm vs. λ and AFR (at fast idling)

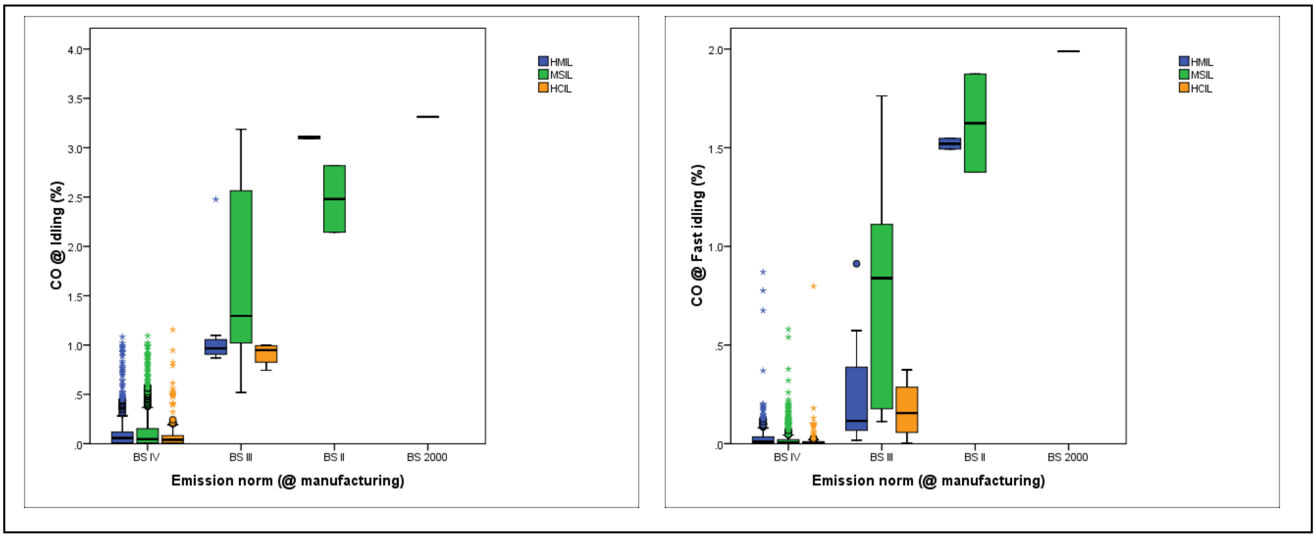


Fig. 4.89 Emission norm vs. CO emission for top 3 makes (at idling and fast idling)

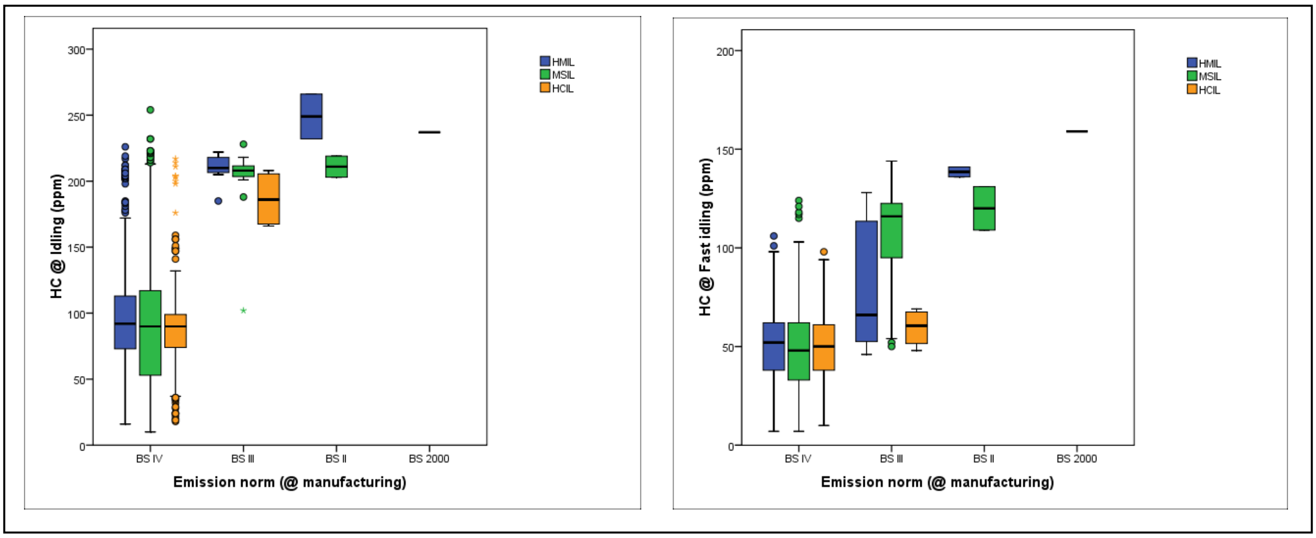


Fig. 4.90 Emission norm vs. HC emission for top 3 makes (at idling and fast idling)

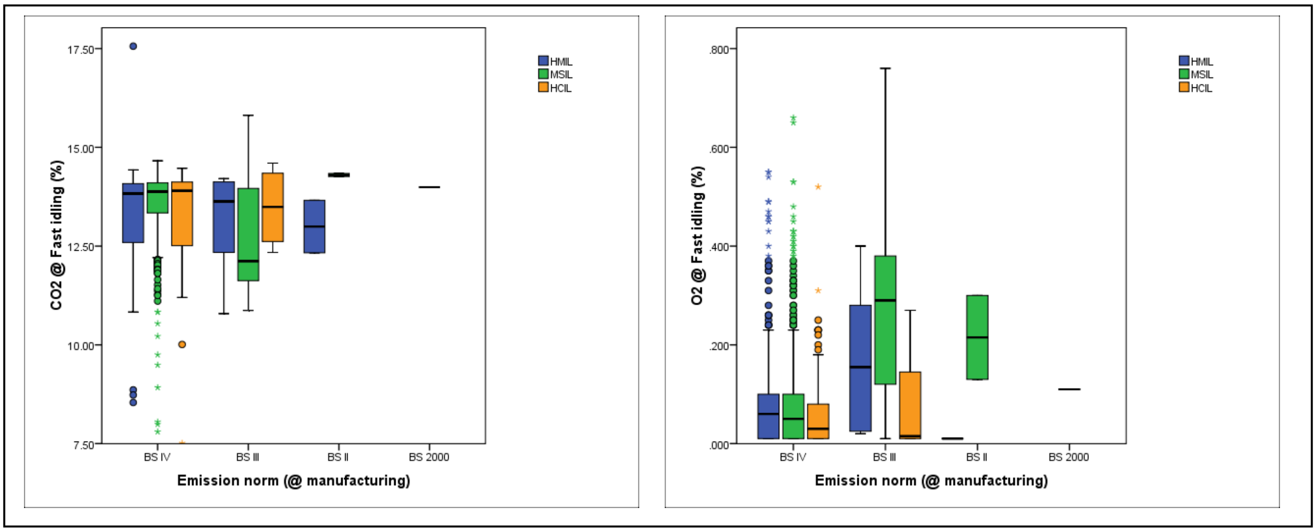


Fig. 4.91 Emission norm vs. CO_2 and O_2 emissions for top 3 makes (at fast idling)

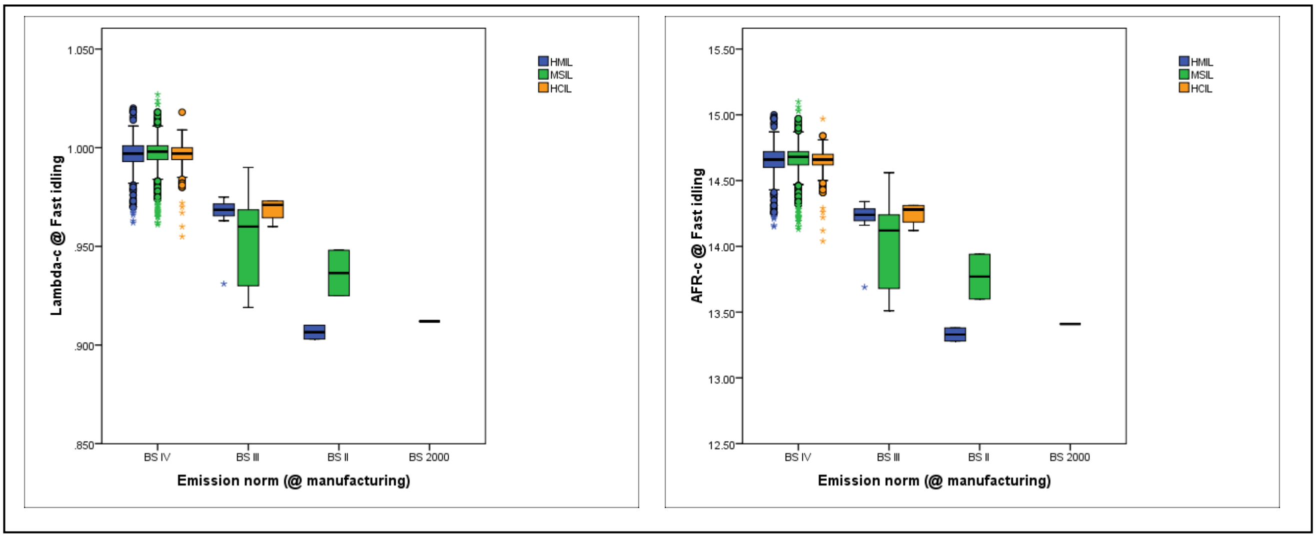


Fig. 4.92 Emission norm vs. λ and AFR for top 3 makes (at fast idling)

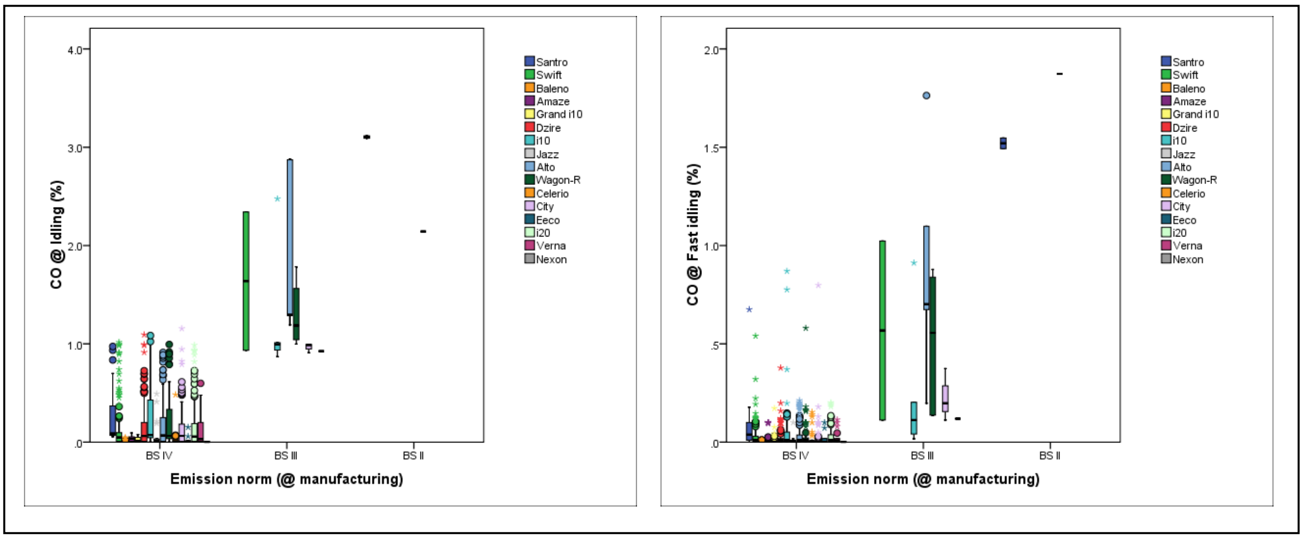


Fig. 4.93 Emission norm vs. CO emission - top 16 models (at idling and fast idling)

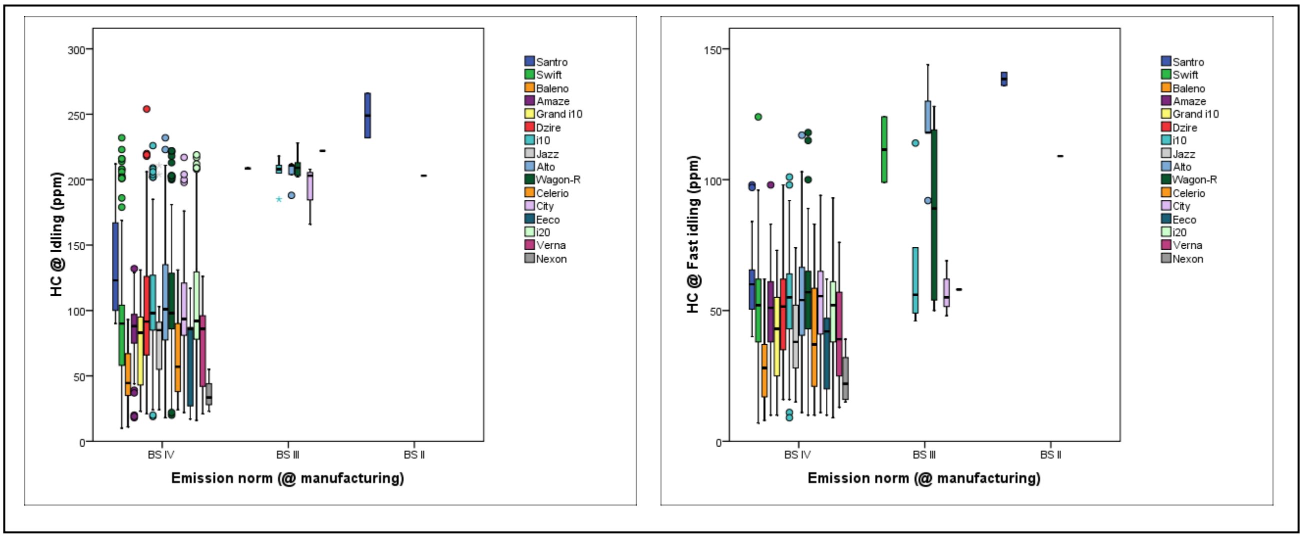


Fig. 4.94 Emission norm vs. HC emission - top 16 models (at idling and fast idling)

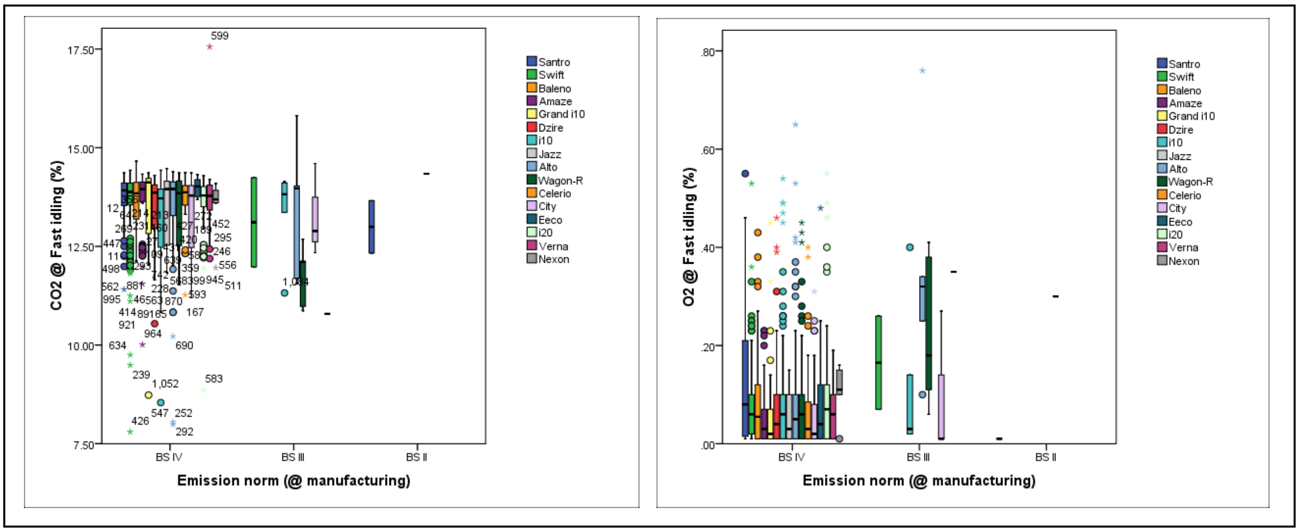


Fig. 4.95 Emission norm vs. CO_2 and O_2 emission - top 16 models (at fast idling)

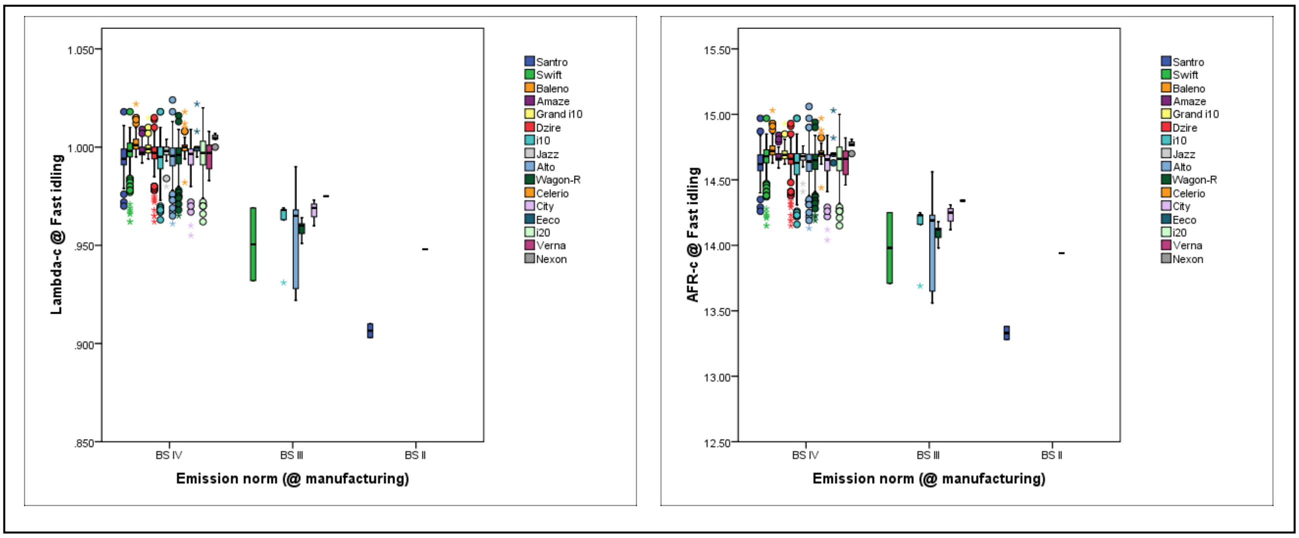


Fig. 4.96 Emission norm vs. λ and AFR - top 16 models (at fast idling)

4.1.1.9 Vehicle maintenance category

The effect of regular inspection and maintenance (I/M) has been reported to be directly related to a vehicle's emission levels. Vehicles with a poor I/M history tend to emit more CO and HC under both idle and fast idle testing conditions and vice-versa (Pandey et al., 2016). The present study aims to reinvestigate the validity of this finding with a larger dataset, a few more tailpipe parameters and also, in respect of different makes and models. The criteria to categorize vehicles based on their number of I/M visits paid to the respective authorized service centres for periodic / casual fitness check over the last two years was used and is presented below (Table 4.21). The criterion considers every two year's frequency of vehicles approaching their respective manufacturer's authorized service centres for fitness tests.

Table 4.21: Criteria for categorization of vehicle's maintenance level

S. No.	No. of fitness visits to manufacture's authorized service centres	Vehicle's maintenance category
1	5 / 6 / 7	Very good
2	3 / 4	Good
3	1-2	Poor
4	0	Unsatisfactory

Boxplots are presented showing the effect of such maintenance categories on tailpipe parameters. It was revealed that the maintenance level has a very apparent and negative correlation with CO and HC emissions under idle and fast idle conditions. The better the maintenance level or higher the number of fitness visits to the authorized service centres, lower the CO and HC levels in the tailpipe exhaust. Although few outliers are visible specially in the case of 'unsatisfactory' and 'good' maintenance category or class of vehicles and more so during fast idling, they do not seem to adversely affect the strong degree of overall lower ranges of emission reducing with betterment in vehicle maintenance category (Figs. 4.97 – 4.98). While CO_2 and O_2 emissions are found not to be affected by maintenance category depicting unchanging ranges, λ and AFR were seen declining with higher number of fitness visits (Figs. 4.99 – 4.100).

In make terms, HCIL depicted the lowest range of CO and HC emissions and the quickest reduction in concentration ranges in both testing conditions with respect to better vehicle maintenance records, followed by MSIL, however, the maximum inconsistency was observed in the case of HMIL, especially in HC @ Fast idling scenario (Figs. 4.101 – 4.102). CO_2, O_2 emissions and λ, AFR values were found to be in line with that depicted in the case of whole dataset (Figs. 4.103 – 4.104). Model-wise analysis showed similar trends as the entire dataset (Figs. 4.105 – 4.108).

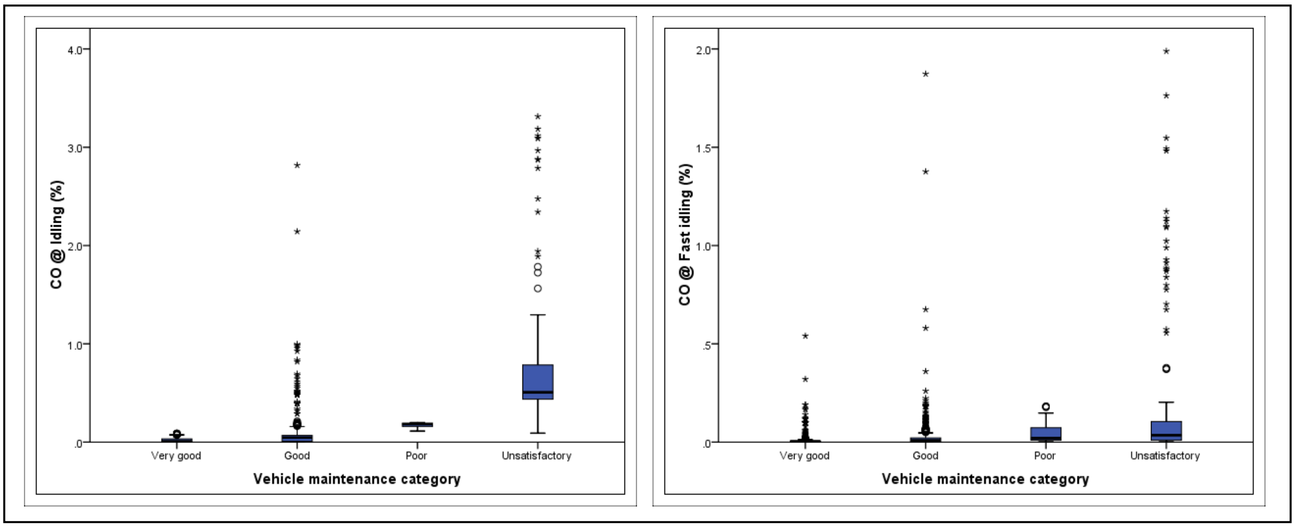


Fig. 4.97 Vehicle maintenance vs. CO emission (at idling and fast idling)

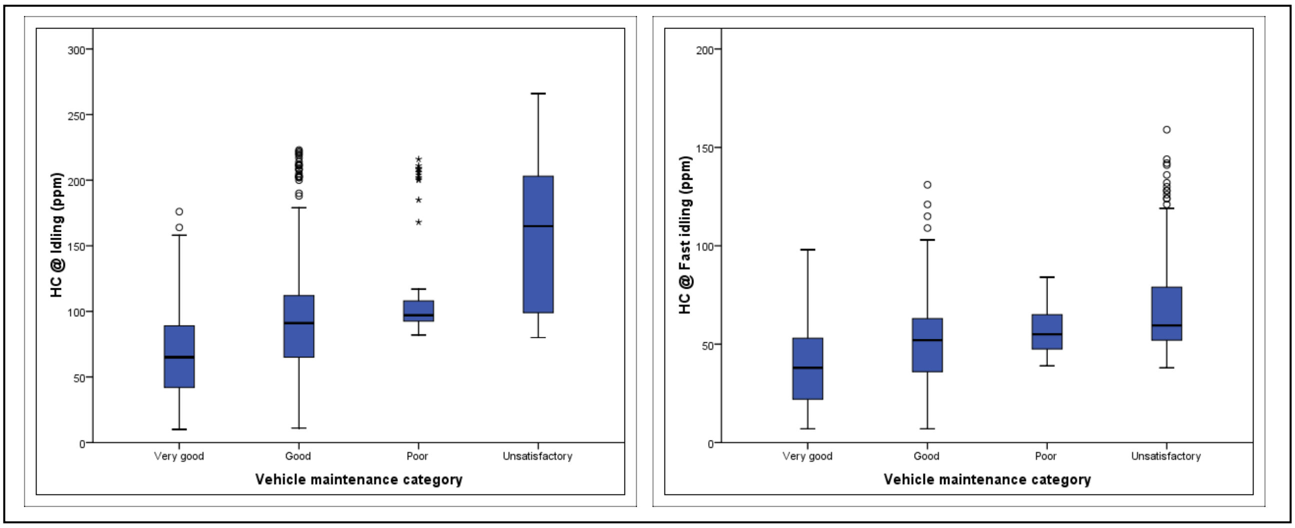


Fig. 4.98 Vehicle maintenance vs. HC emission (at idling and fast idling)

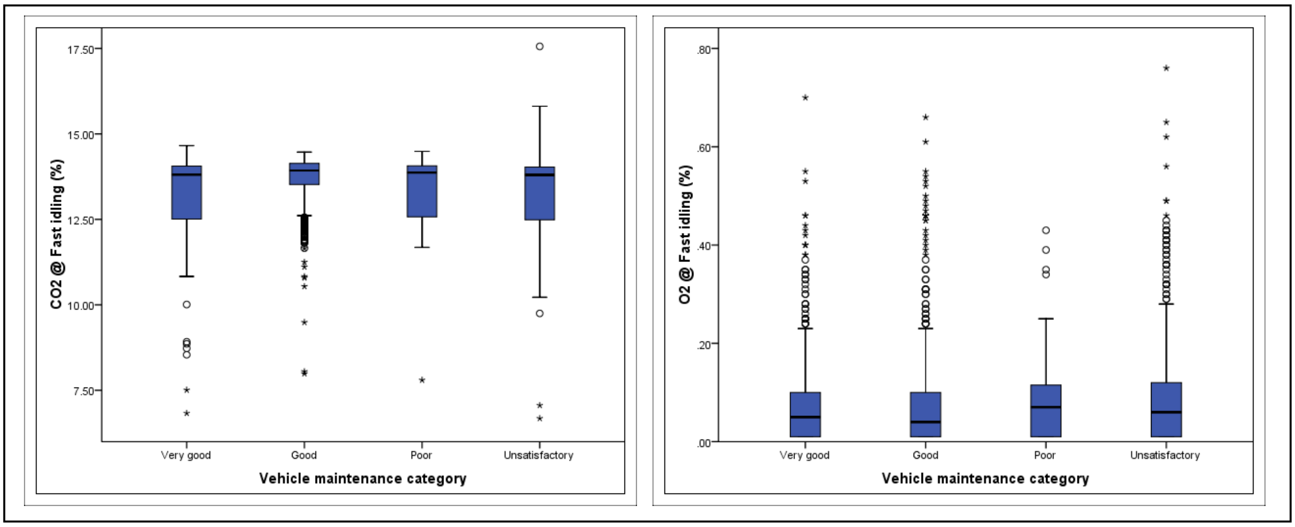


Fig. 4.99 Vehicle maintenance vs. CO_2 and O_2 emissions (at fast idling)

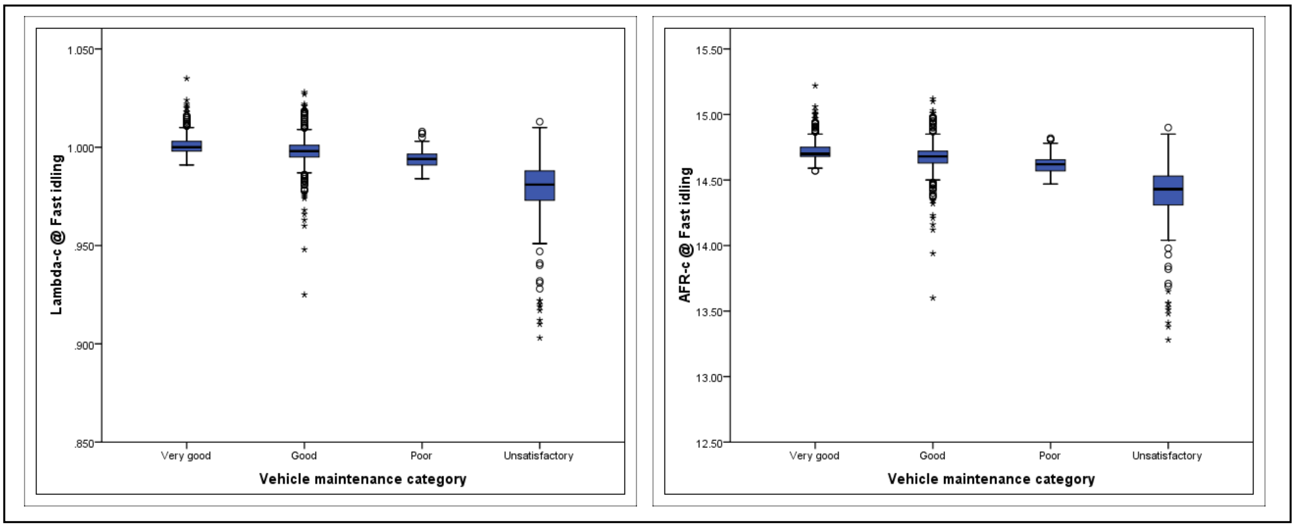


Fig. 4.100 Vehicle maintenance vs. λ and AFR (at fast idling)

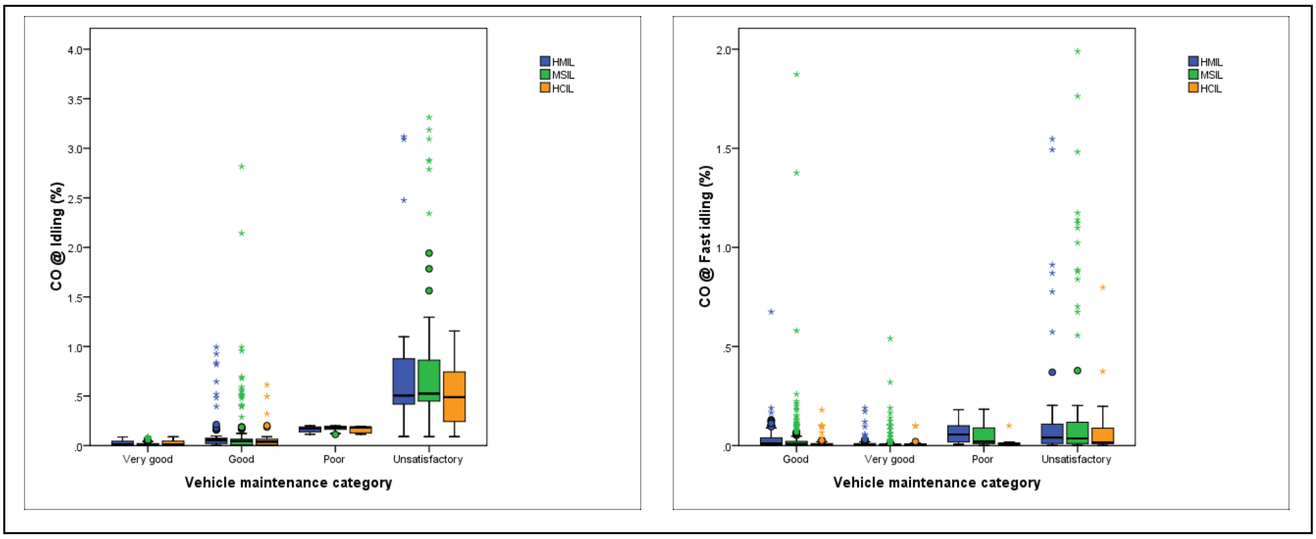


Fig. 4.101 Vehicle maintenance vs. CO emission - top 3 makes (at idling and fast idling)

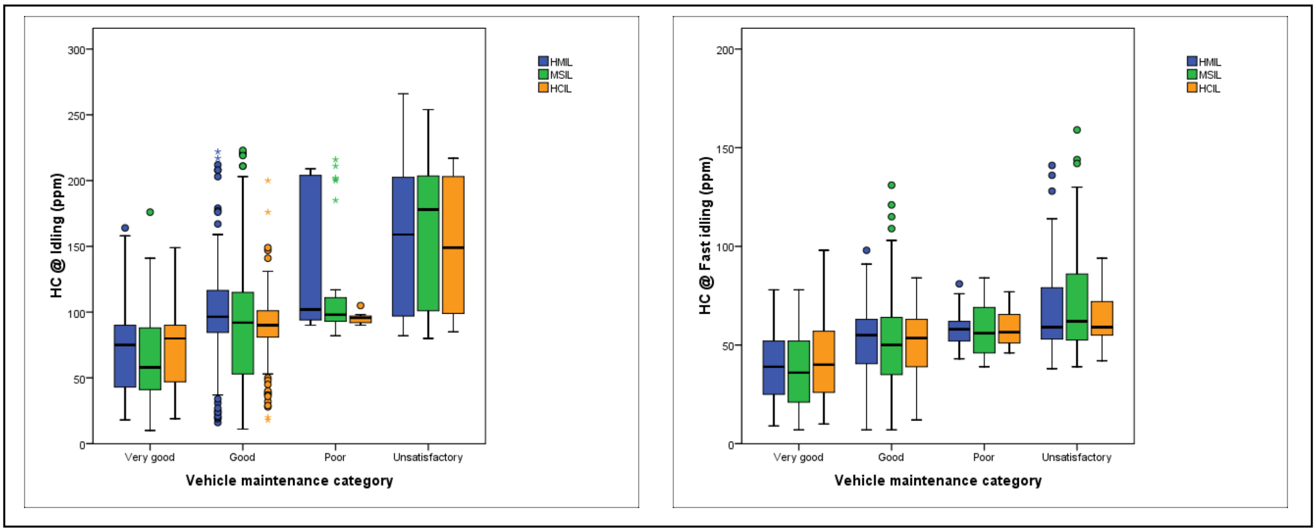


Fig. 4.102 Vehicle maintenance vs. HC emission - top 3 makes (at idling and fast idling)

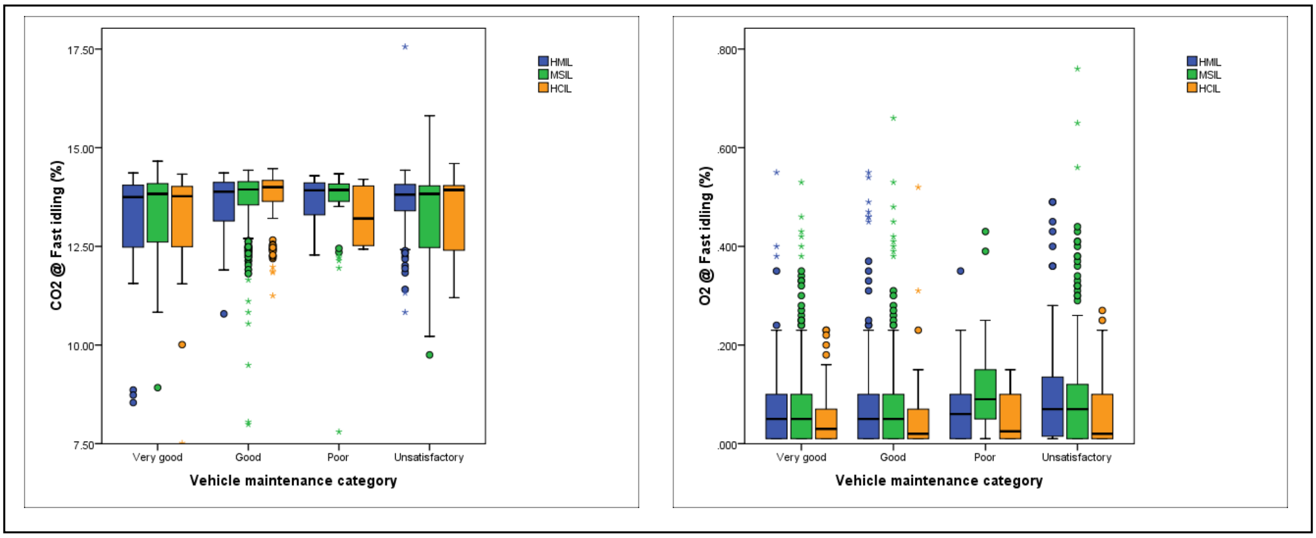


Fig. 4.103 Vehicle maintenance vs. CO_2 and O_2 emissions - top 3 makes (at fast idling)

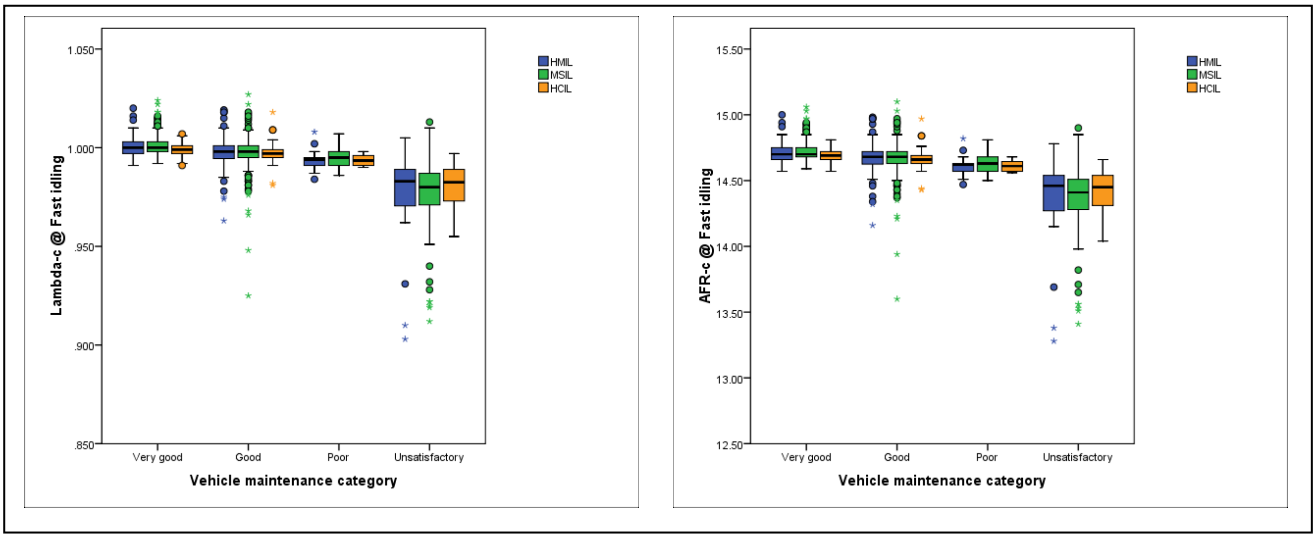


Fig. 4.104 Vehicle maintenance vs. λ and AFR - top 3 makes (at fast idling)

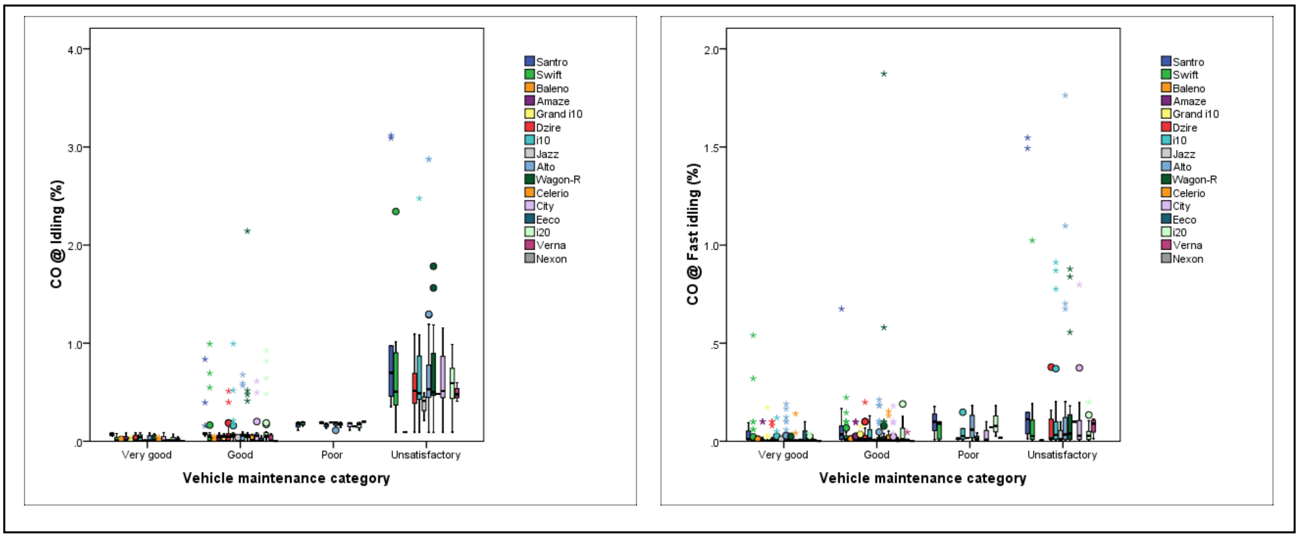


Fig. 4.105 Vehicle maintenance vs. CO emission - top 16 models (at idling and fast idling)

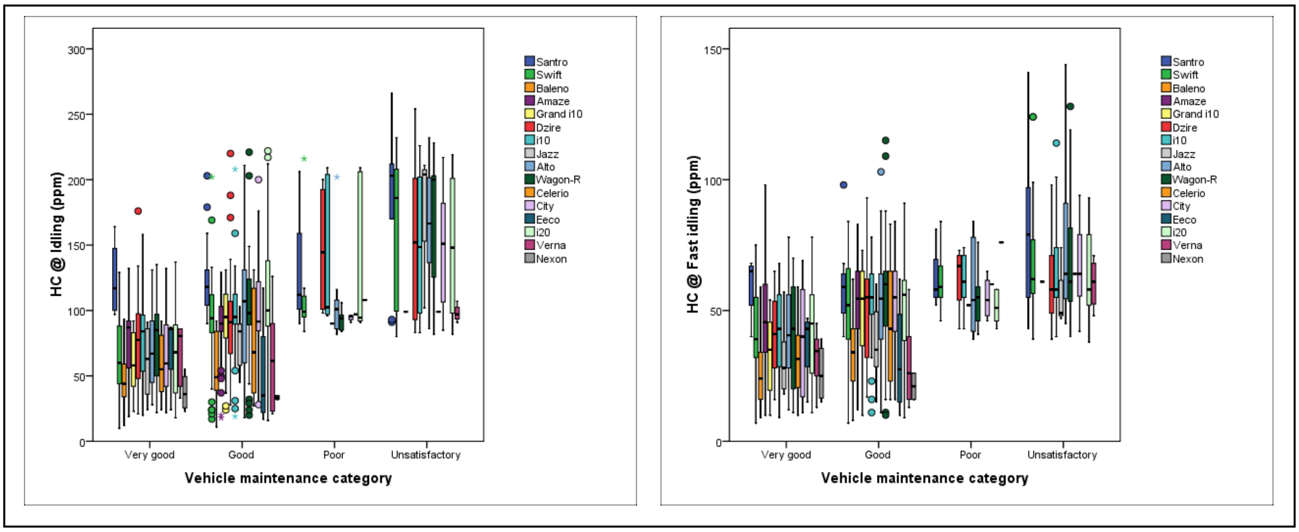


Fig. 4.106 Vehicle maintenance vs. HC emission - top 16 models (at idling and fast idling)

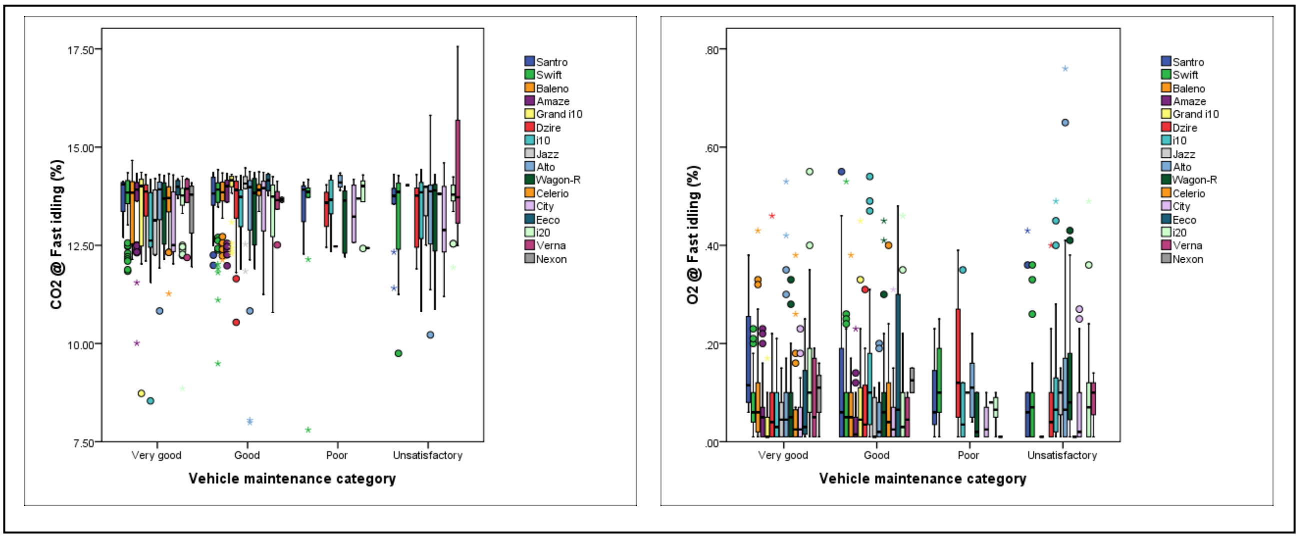


Fig. 4.107 Vehicle maintenance vs. CO_2 and O_2 emission - top 16 models (at fast idling)

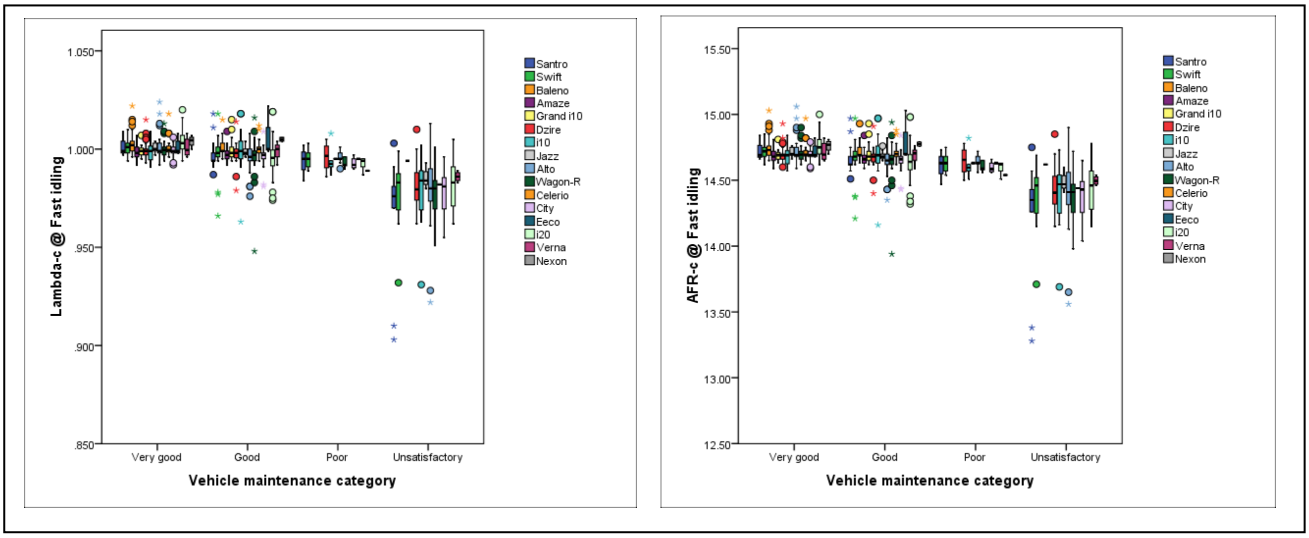


Fig. 4.108 Vehicle maintenance vs. λ and AFR - top 16 models (at fast idling)

4.1.1.10 Effect of engine-related variables on tailpipe emission / parameters

The study also attempted to investigate the effect(s) of various engine-specific variables (scale and / or strings type datapoints) on tailpipe emission parameters, such as, Engine capacity (cc), Maximum power (bhp), Maximum torque (Nm), Compression ratio (:1), Cylinder bore (mm) and piston stroke (mm), Engine aspiration type (Natural or Turbo-charged), Number of cylinders, Number of valves per cylinder, Valve configuration (SOHC – Single overhead cam or DOHC – Double overhead cam) and Fuel mixing conditions (Rich or Lean or Stoichiometric).

It is revealed that engine variables, namely, engine capacity, maximum power, maximum torque, cylinder bore and piston stroke, number of cylinders, number of valves per cylinder and valve configuration do not seem to be related to tailpipe exhaust (CO, HC, CO_2 and O_2) or other parameters, such as λ and AFR. The variables were analyzed using scatter plots (having continuous variables for vehicles / cases, e.g., engine capacity, maximum power, maximum torque, compression ratio, cylinder bore and piston stroke) and checked for R^2 values yielded by quadratic trendlines in order to explore correlation, if any. Boxplots were drawn for string variables at nominal scale for cases like number of cylinders, number of valves per cylinder, engine aspiration, valve configuration and fuel mixing conditions) and assessed for any specific pattern of change in measured values of dependent variables' ranges with respect to said engine variables.

The set of scatter and boxplots for the engine-related variables were also drawn for the top 3 makes and top 16 models and analyzed to ascertain if there existed any correlation or visible pattern in the change of measured datapoints make or model-wise. The data analysis revealed that these engine-related aspects are not related to tailpipe parameters even in the case of make and models addressed in the present study. The R^2 values and the boxplot layouts were found to be too low to point towards any reliable correlation (Fig. 4.109 – 4.208). Due to the interface restrictions in SPSS program, the cylinder bore and piston stroke in respect of all eight dependent variables (i.e., CO @ Idling, CO @ Fast idling, HC @ Idling, HC @ Fast idling, CO_2, O_2, λ and AFR- all @ Fast idling) were presented in two different plot styles – in dual axes mode for the whole dataset and individual x-axis mode for makes and models. Similar was the case for boxplots drawn for the number of cylinders and valves per cylinder in three different datasets.

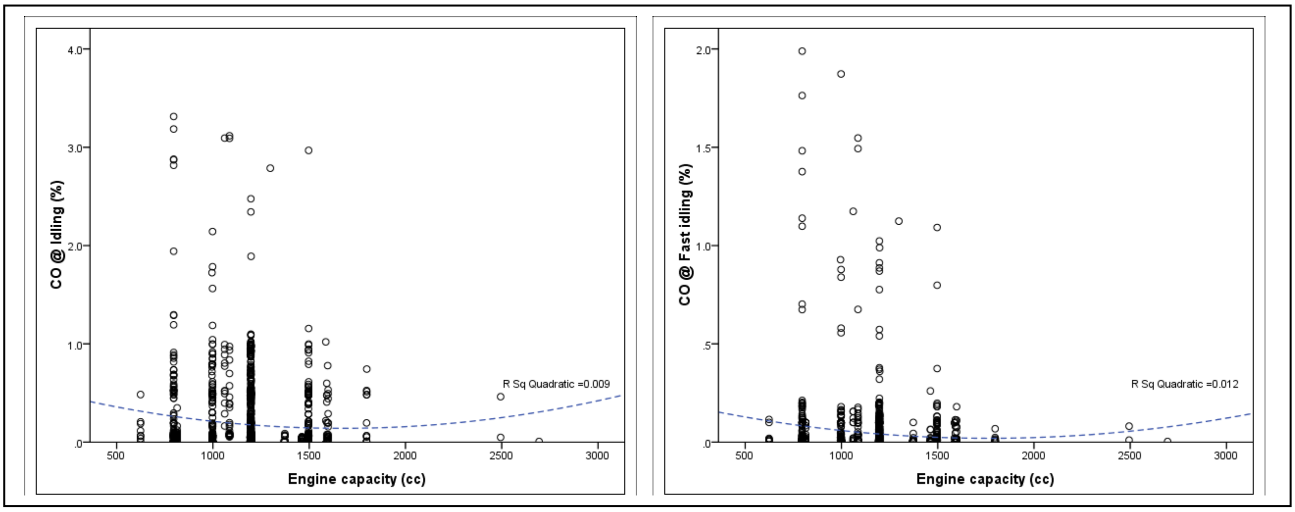


Fig. 4.109 Engine capacity vs. CO emission (at idling and fast idling)

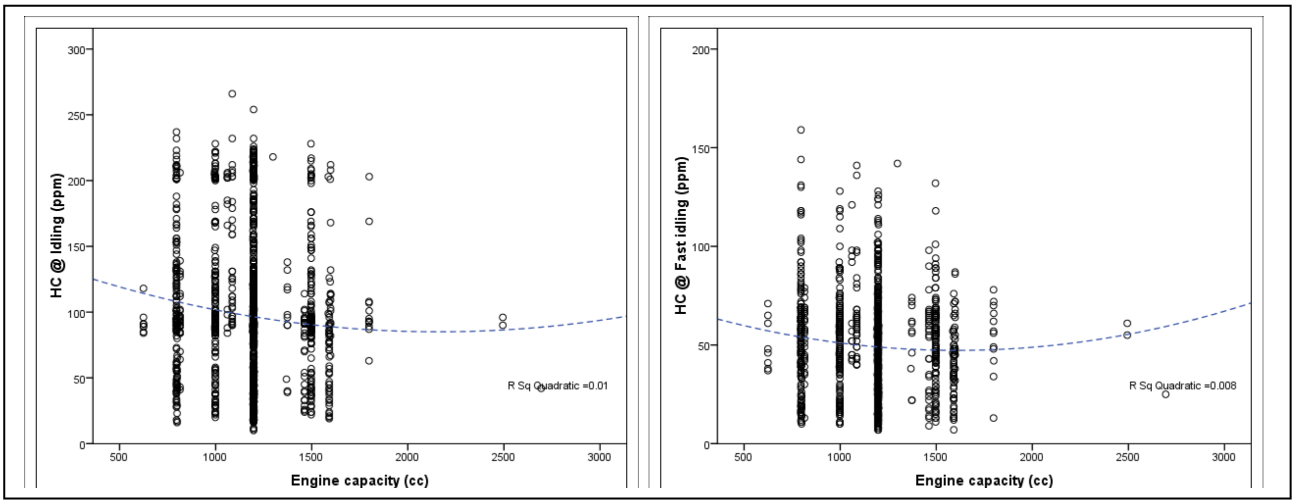


Fig. 4.110 Engine capacity vs. HC emission (at idling and fast idling)

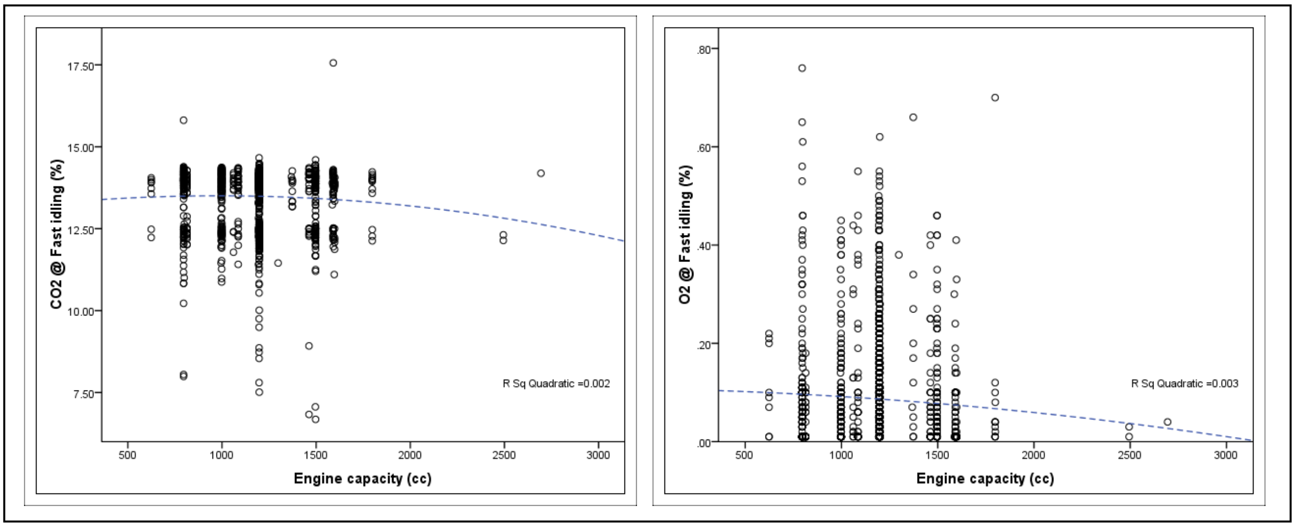


Fig. 4.111 Engine capacity vs. CO_2 and O_2 emissions (at fast idling)

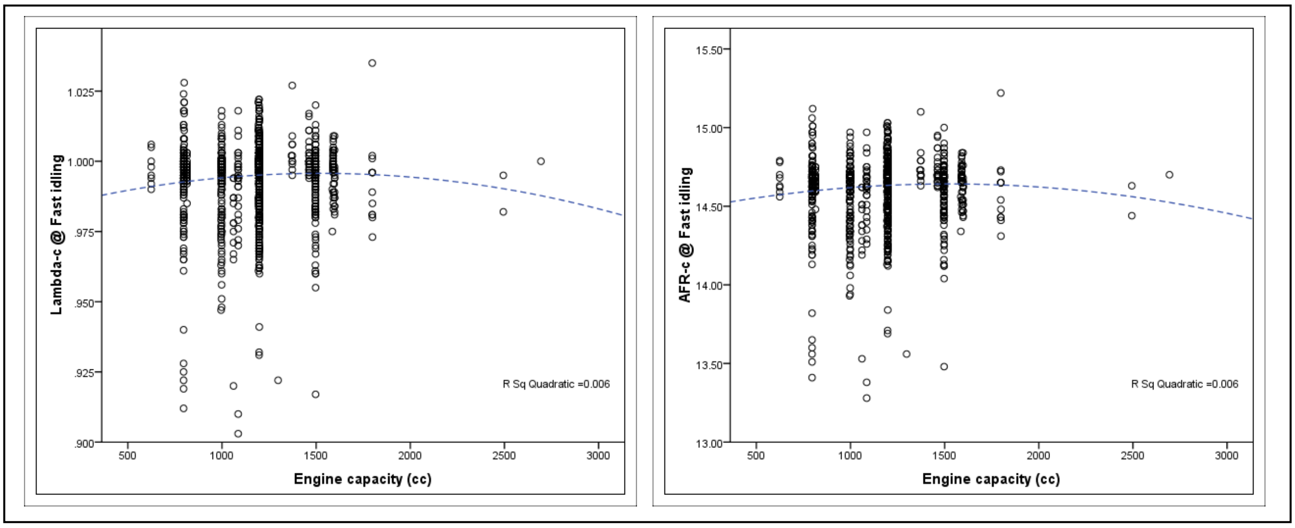


Fig. 4.112 Engine capacity vs. λ and AFR (at fast idling)

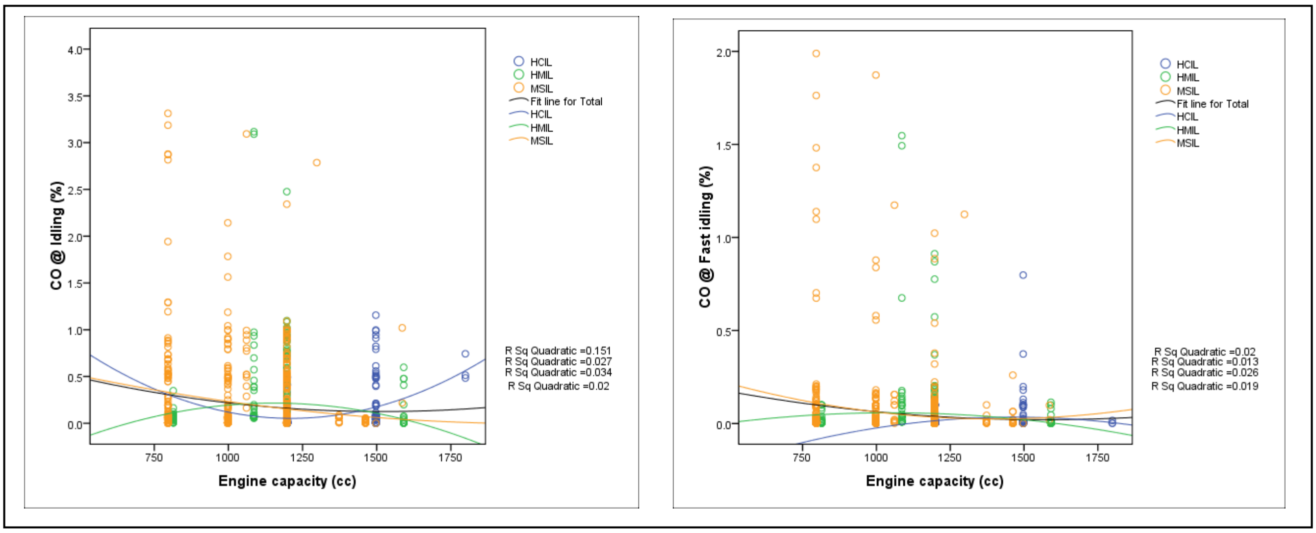


Fig. 4.113 Engine capacity vs. CO emission - top 3 makes (at idling and fast idling)

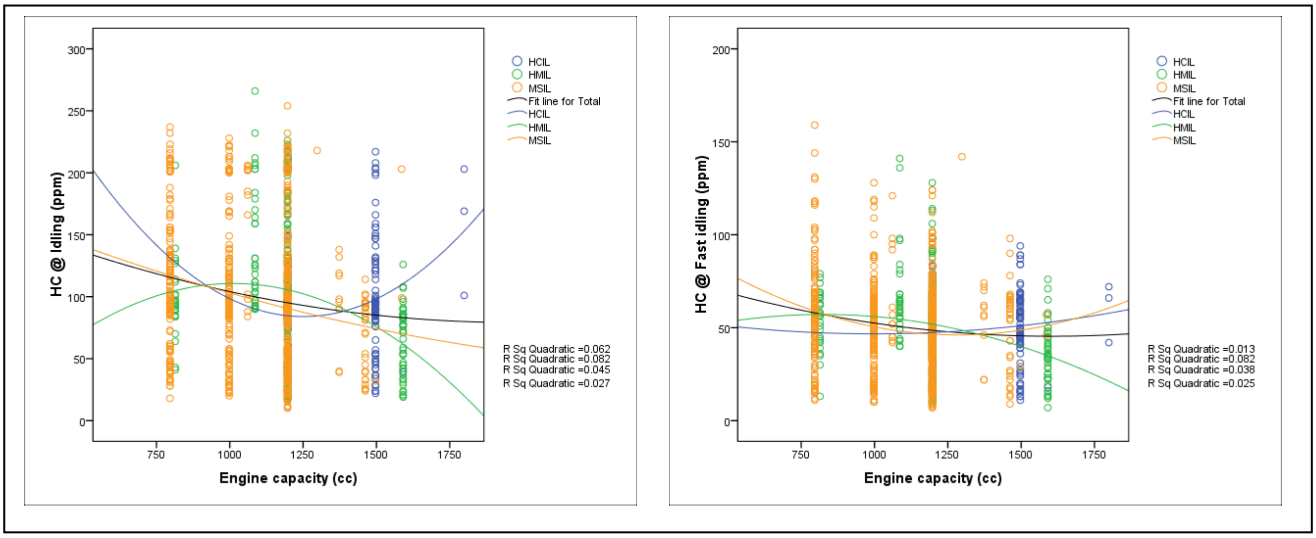


Fig. 4.114 Engine capacity vs. HC emission - top 3 makes (at idling and fast idling)

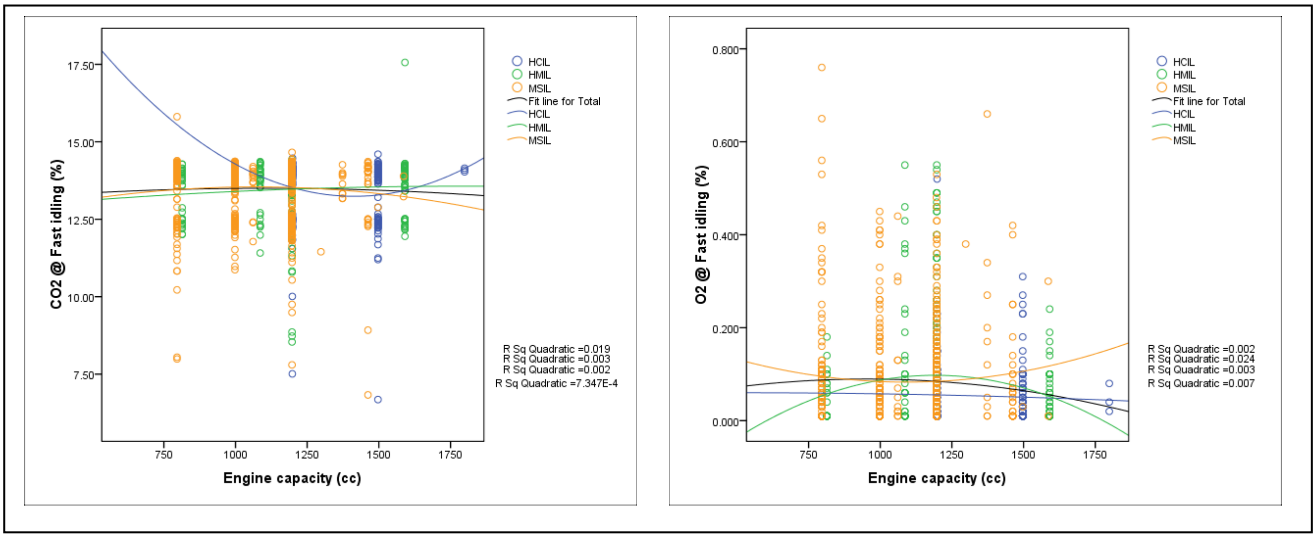


Fig. 4.115 Engine capacity vs. CO_2 and O_2 emissions - top 3 makes (at fast idling)

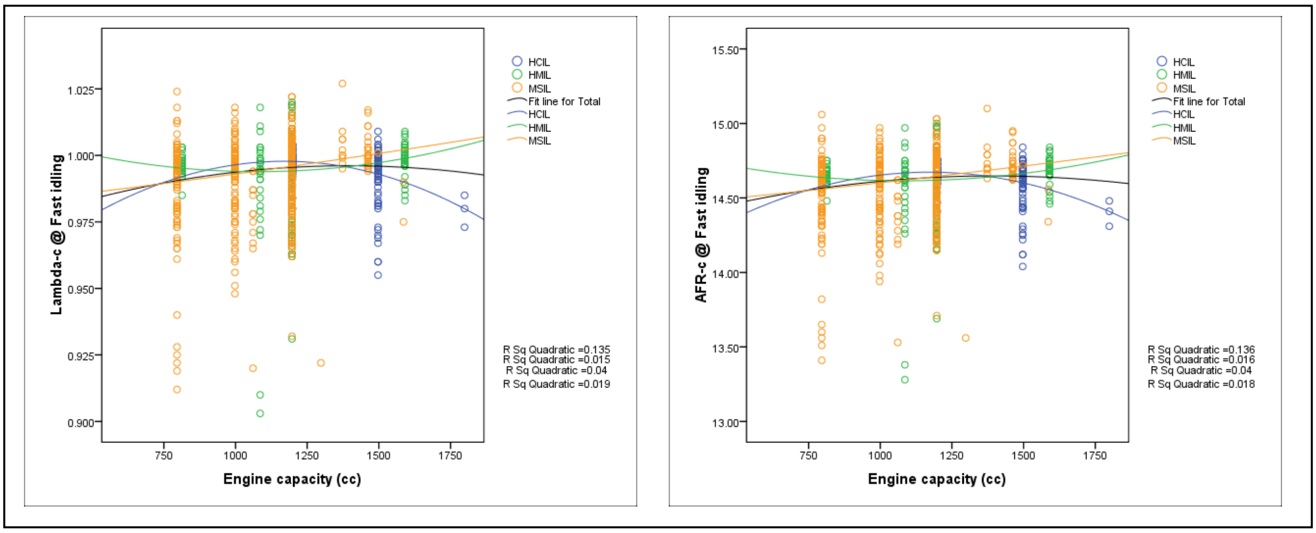


Fig. 4.116 Engine capacity vs. λ and AFR - top 3 makes (at fast idling)

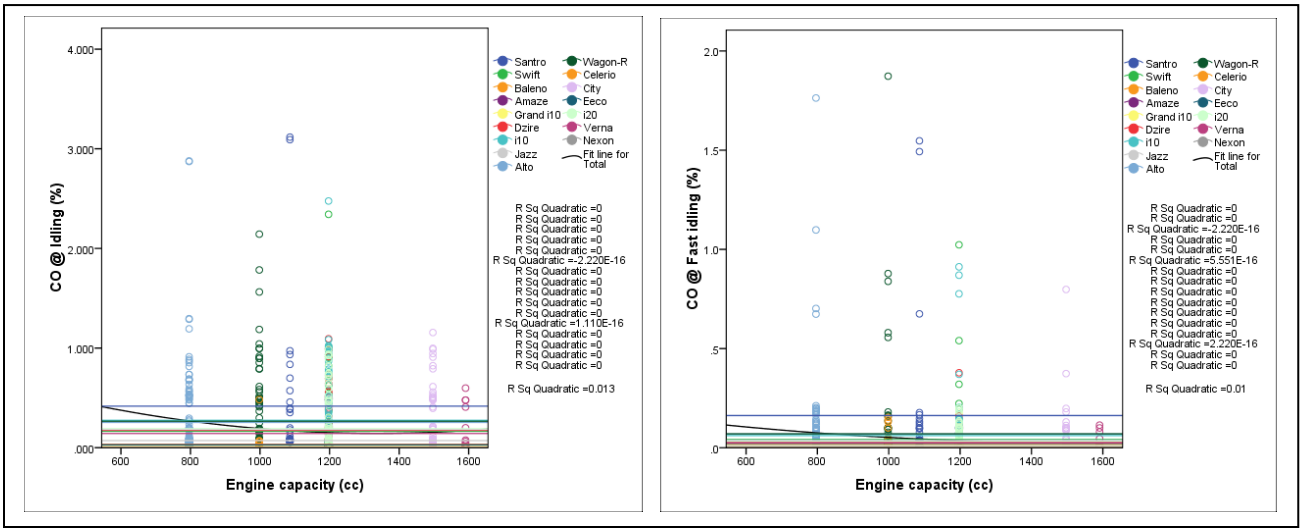


Fig. 4.117 Engine capacity vs. CO emission - top 16 models (at idling and fast idling)

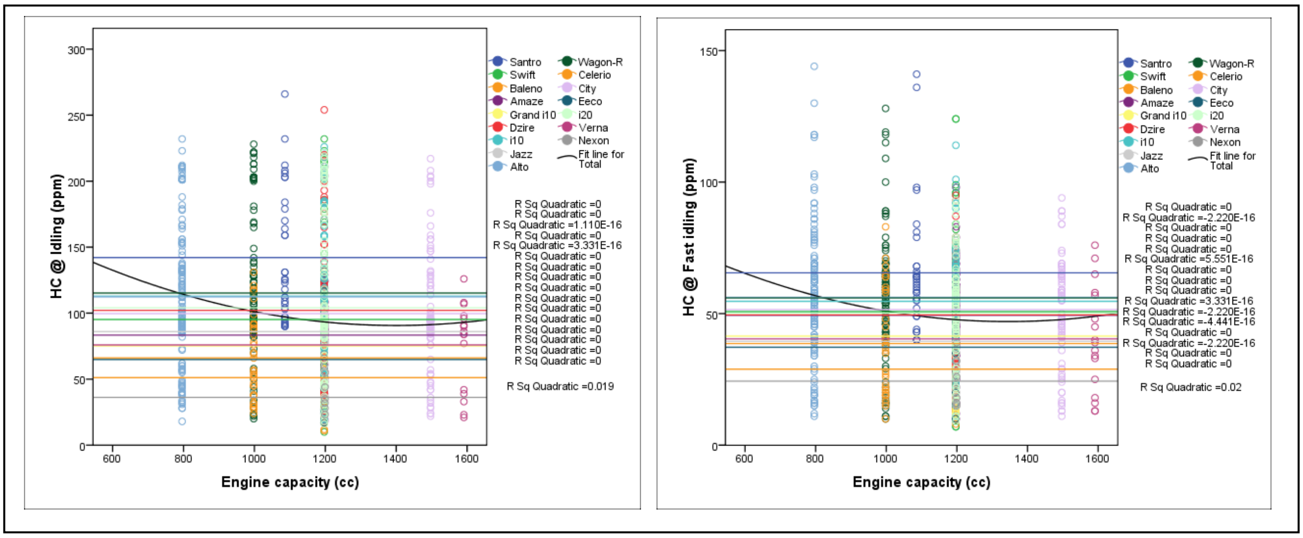


Fig. 4.118 Engine capacity vs. HC emission - top 16 models (at idling and fast idling)

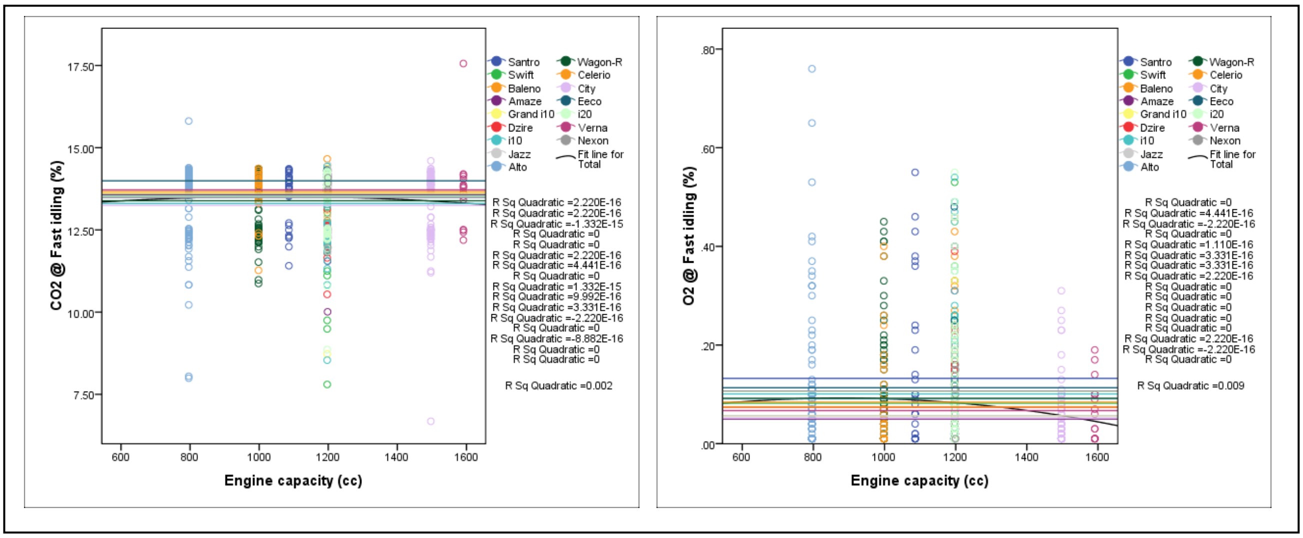


Fig. 4.119 Engine capacity vs. CO$_2$ and O$_2$ emission - top 16 models (at fast idling)

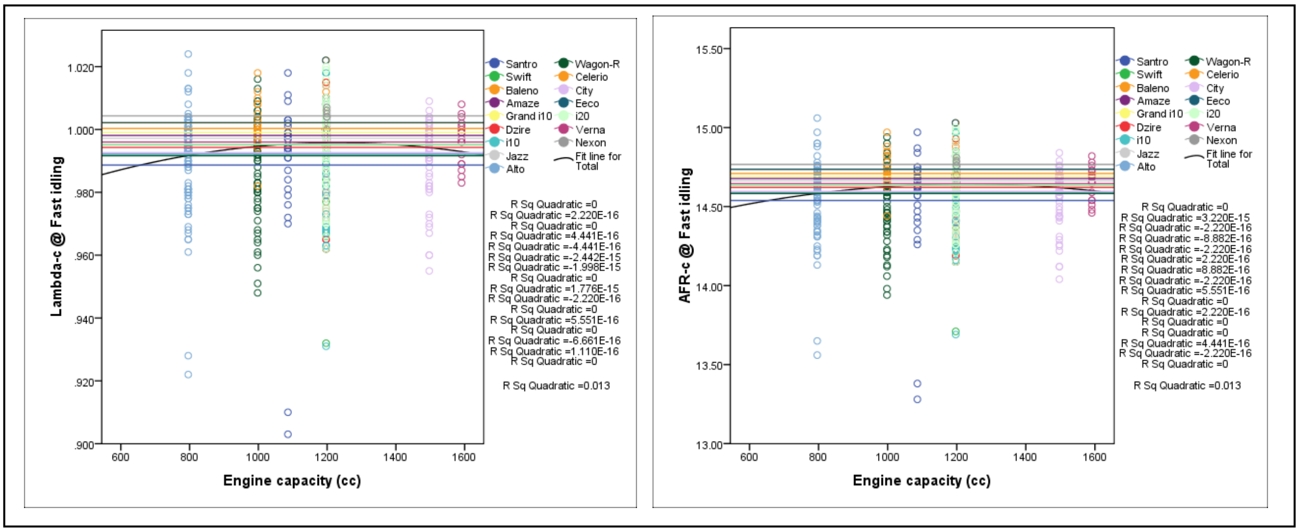


Fig. 4.120 Engine capacity vs. λ and AFR - top 16 models (at fast idling)

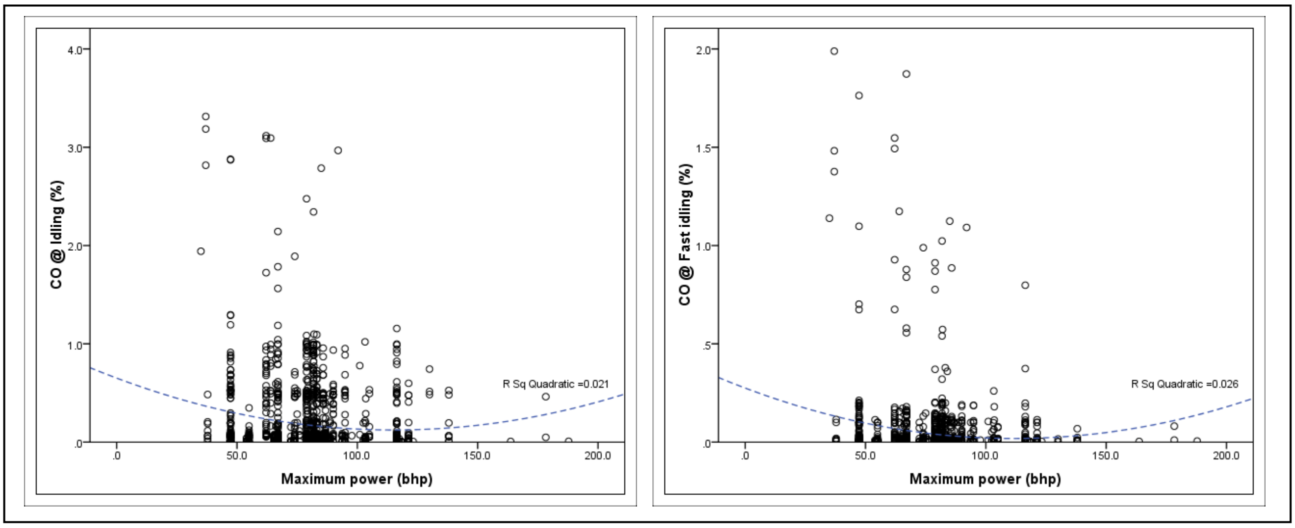


Fig. 4.121 Maximum power vs. CO emission (at idling and fast idling)

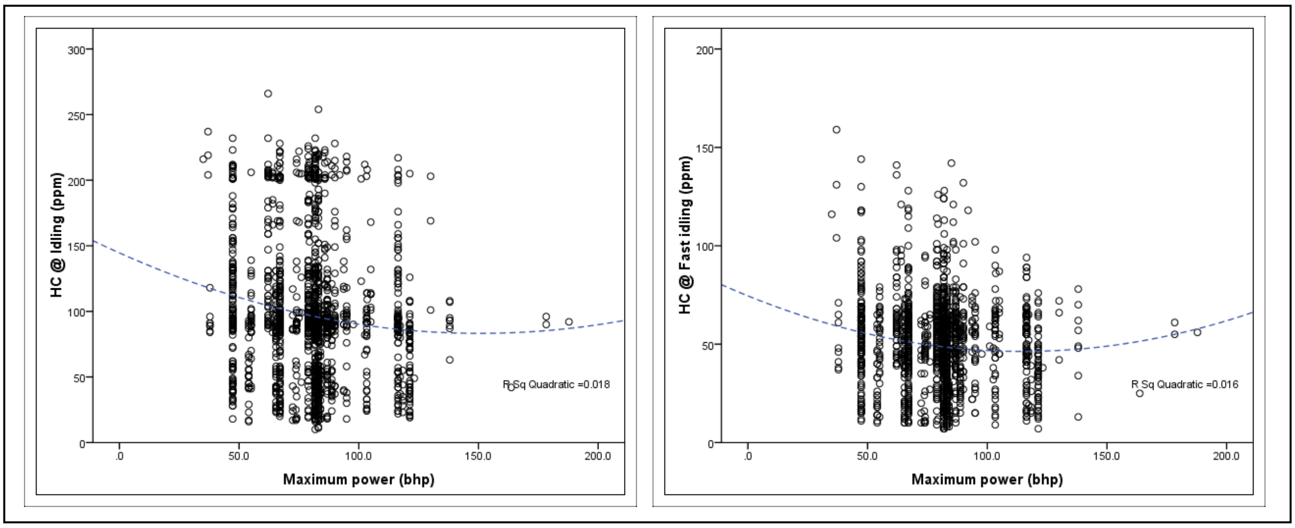


Fig. 4.122 Maximum power vs. HC emission (at idling and fast idling)

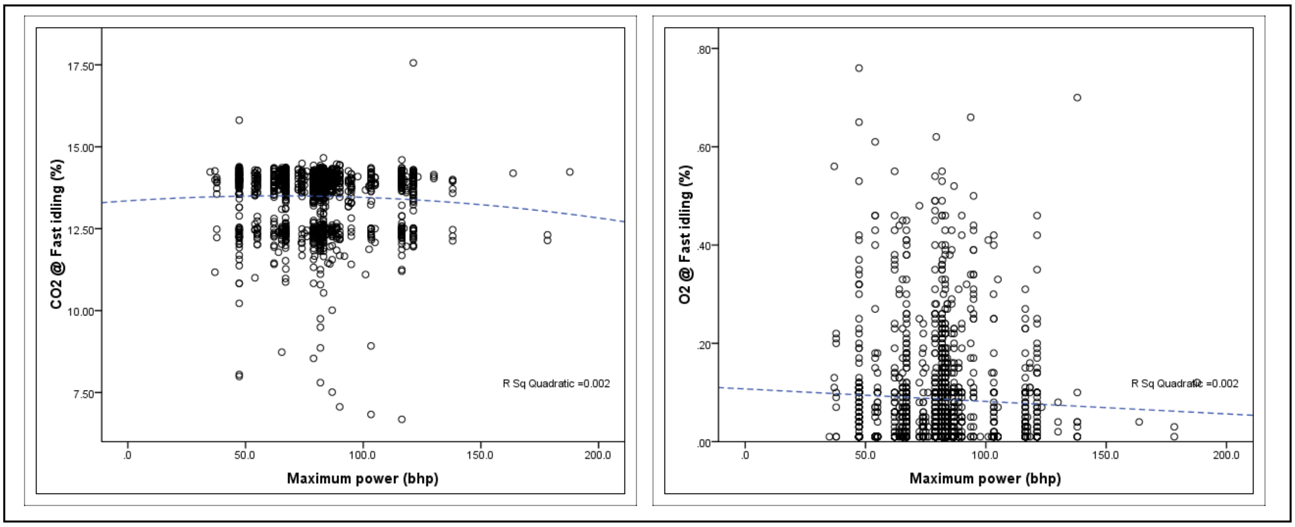


Fig. 4.123 Maximum power vs. CO_2 and O_2 emissions (at fast idling)

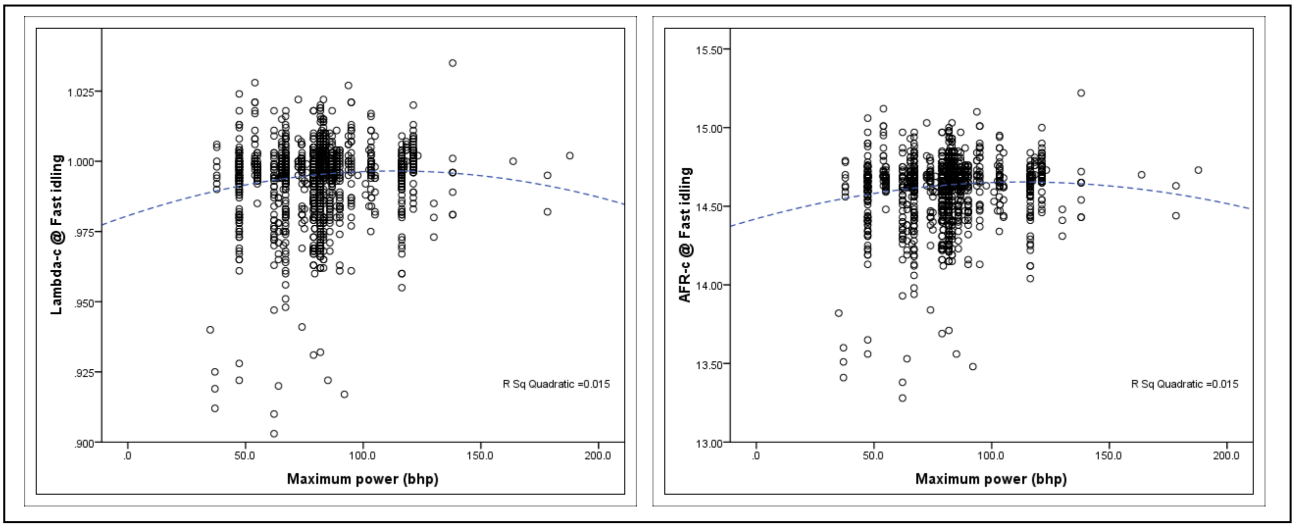


Fig. 4.124 Maximum power vs. λ and AFR (at fast idling)

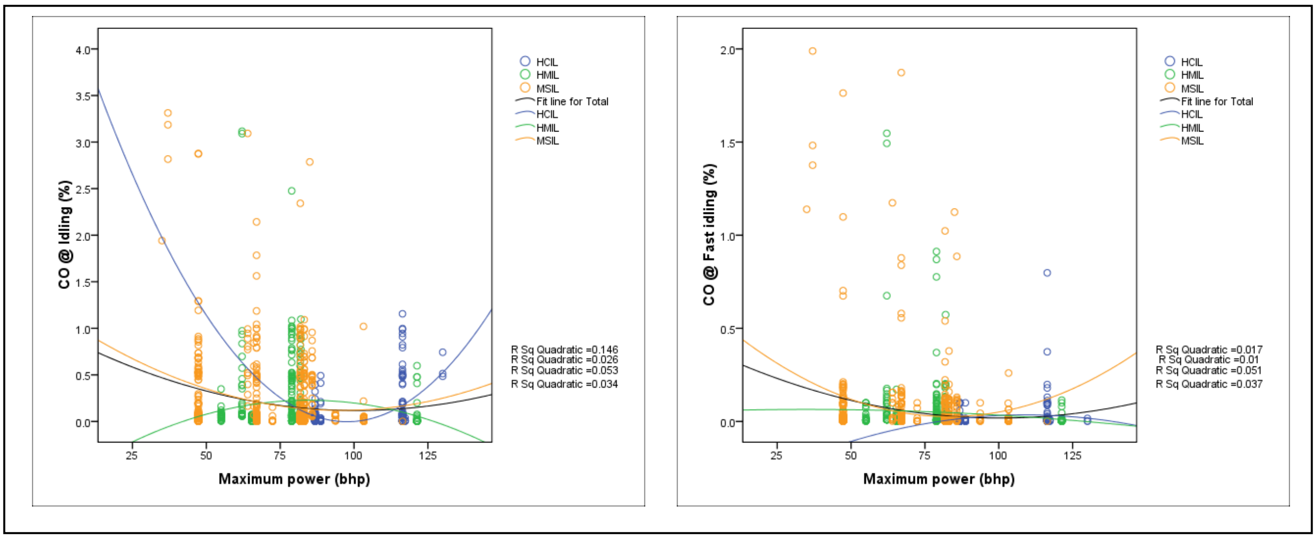


Fig. 4.125 Maximum power vs. CO emission - top 3 makes (at idling and fast idling)

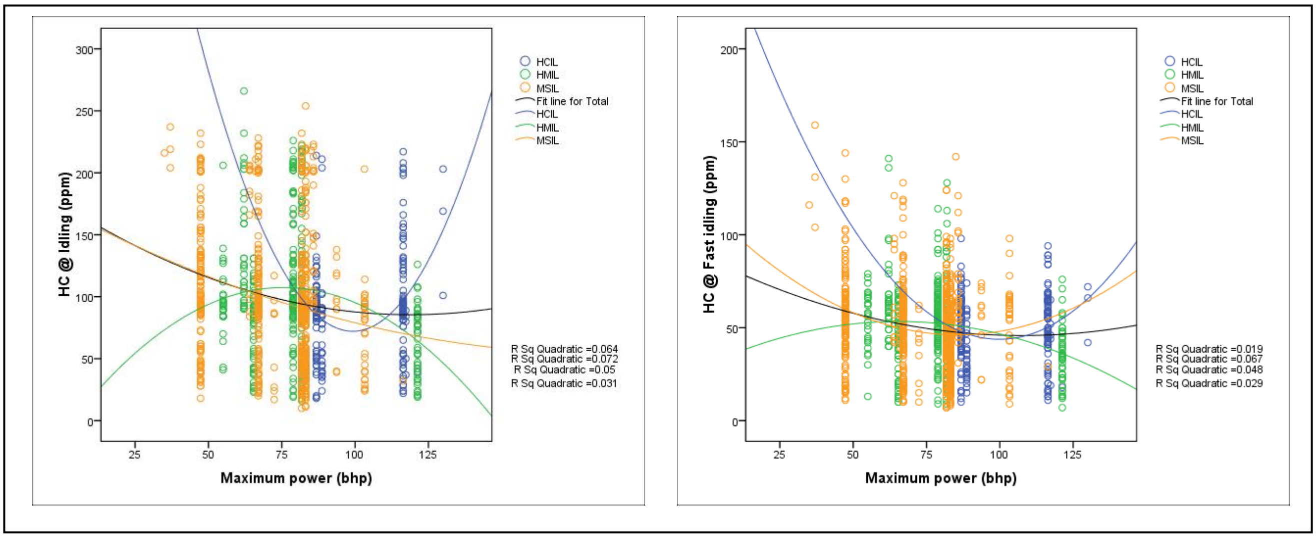


Fig. 4.126 Maximum power vs. HC emission - top 3 makes (at idling and fast idling)

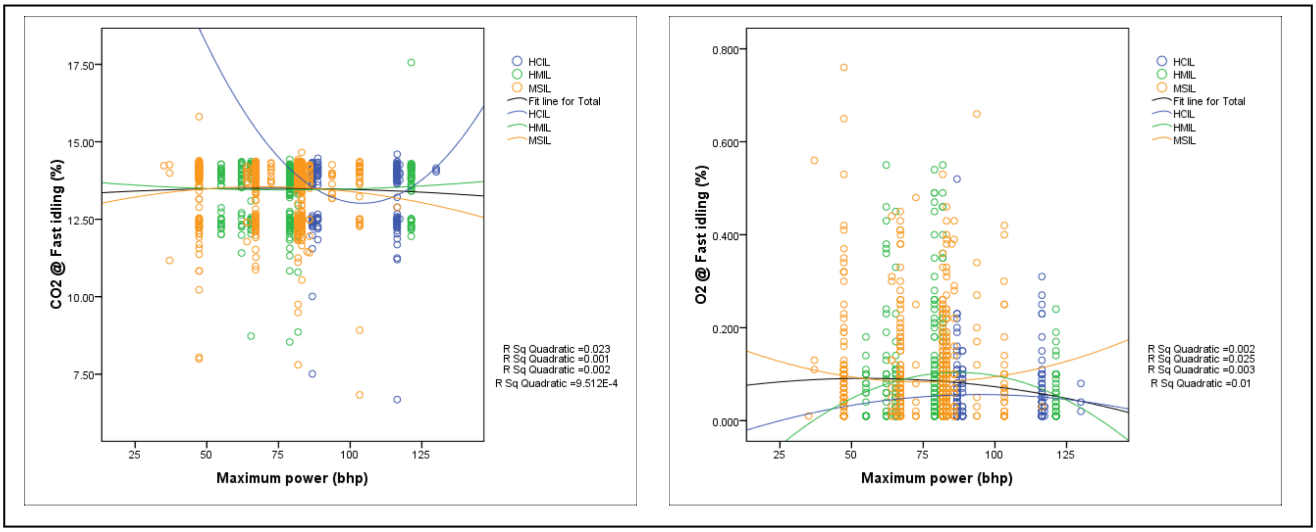


Fig. 4.127 Maximum power vs. CO_2 and O_2 emissions - top 3 makes (at fast idling)

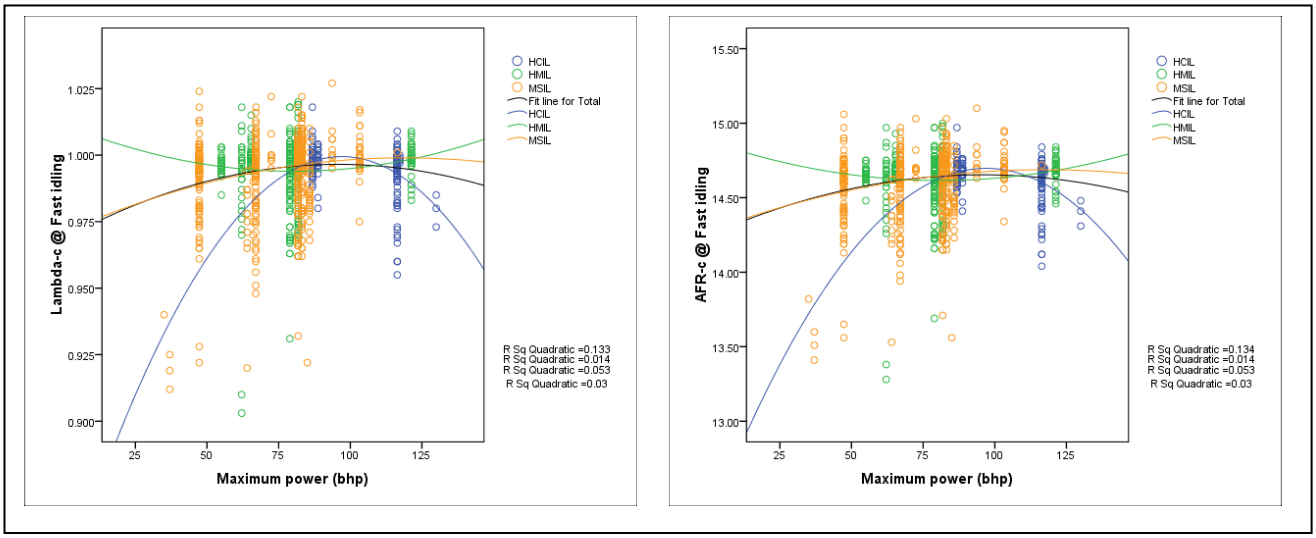


Fig. 4.128 Maximum power vs. λ and AFR - top 3 makes (at fast idling)

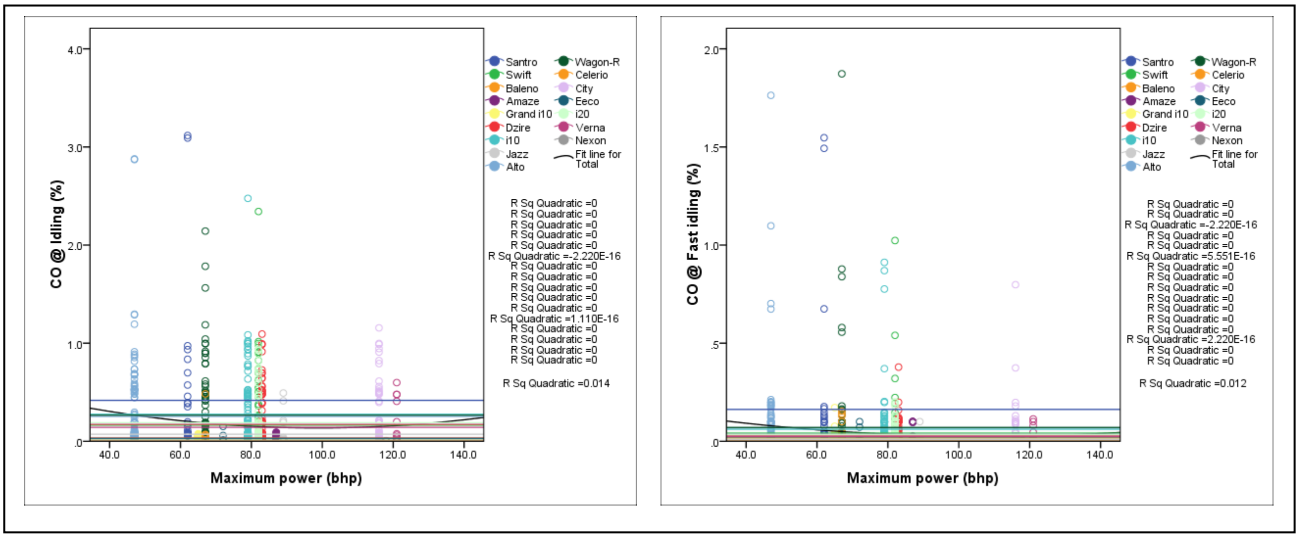


Fig. 4.129 Maximum power vs. CO emission - top 16 models (at idling and fast idling)

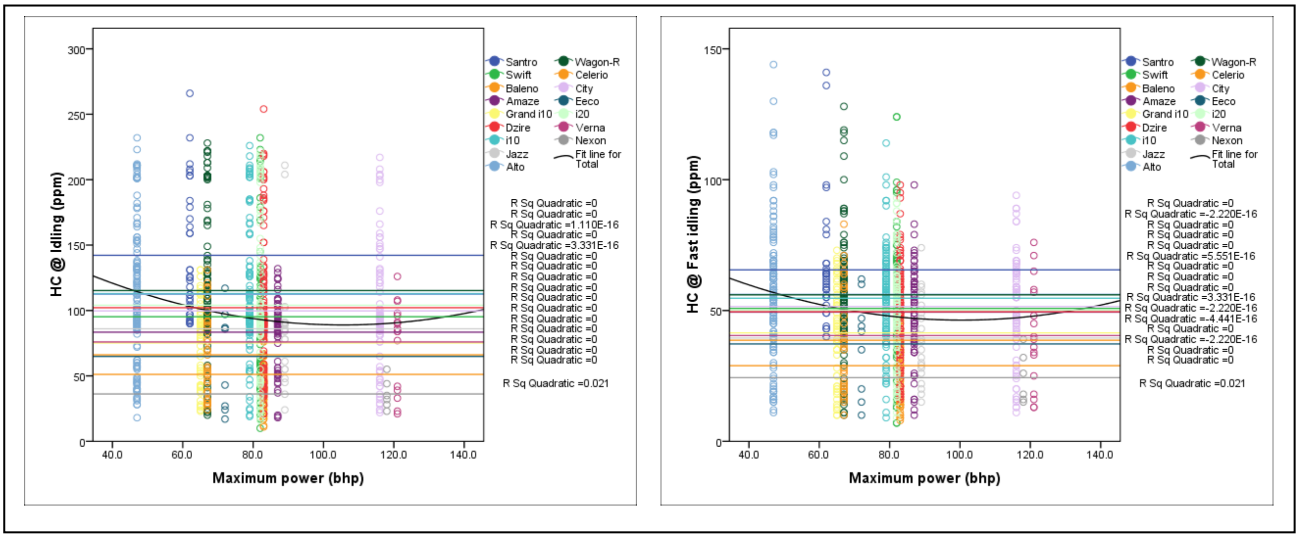


Fig. 4.130 Maximum power vs. HC emission - top 16 models (at idling and fast idling)

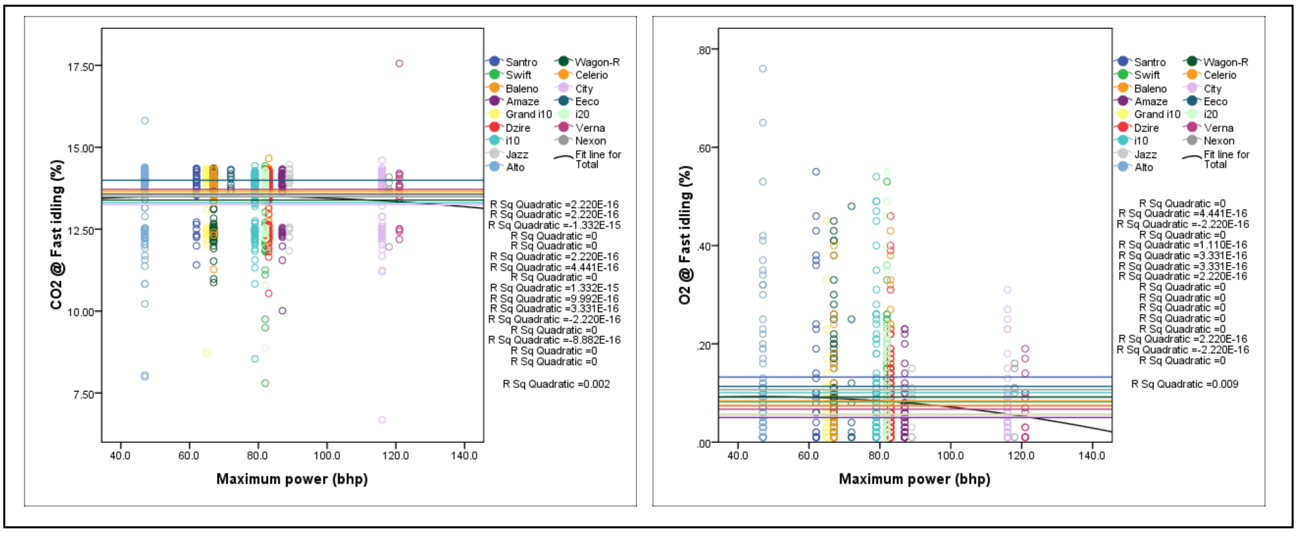


Fig. 4.131 Maximum power vs. CO_2 and O_2 emission - top 16 models (at fast idling)

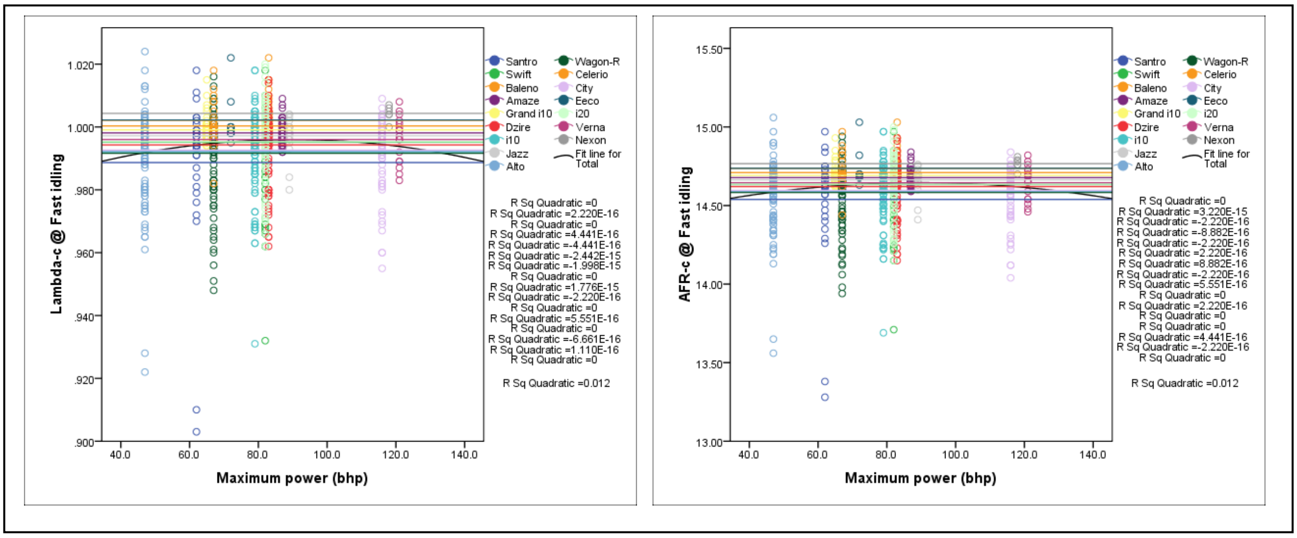


Fig. 4.132 Maximum power vs. λ and AFR - top 16 models (at fast idling)

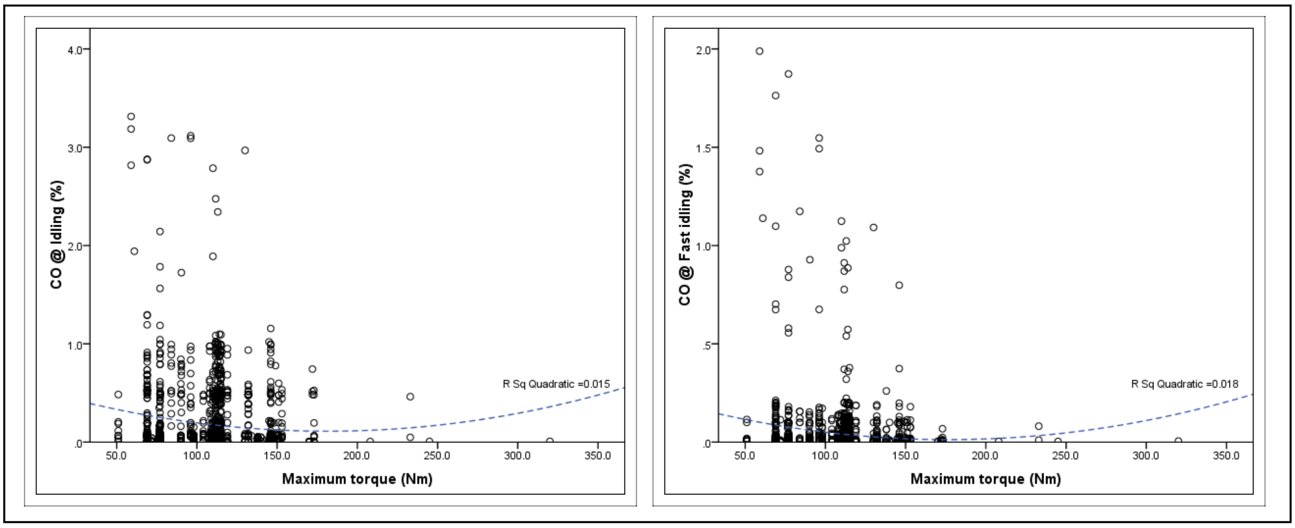


Fig. 4.133 Maximum torque vs. CO emission (at idling and fast idling)

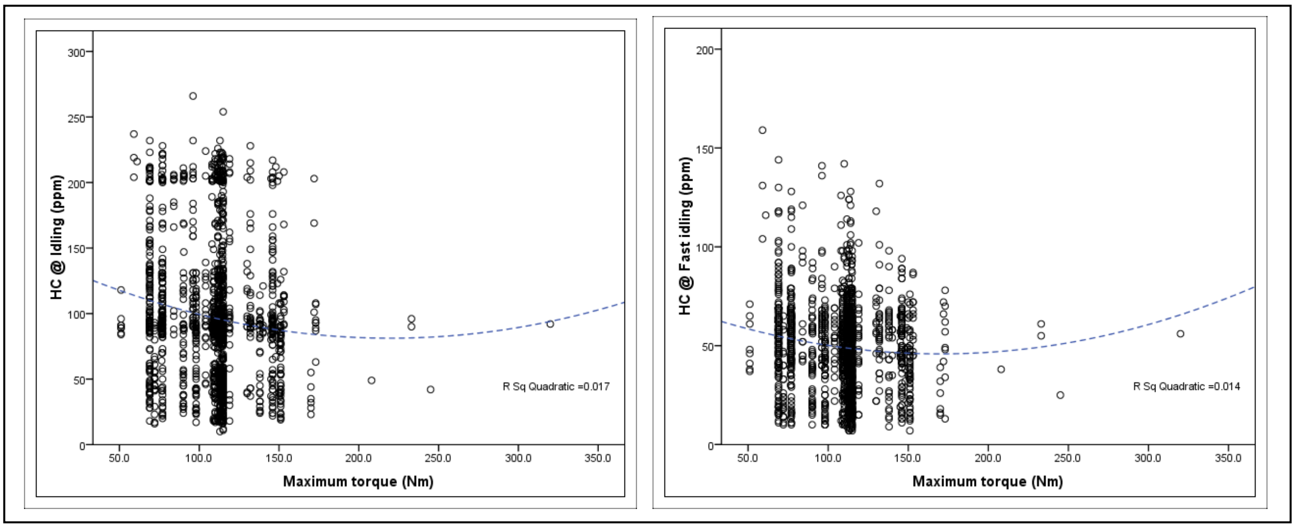


Fig. 4.134 Maximum torque vs. HC emission (at idling and fast idling)

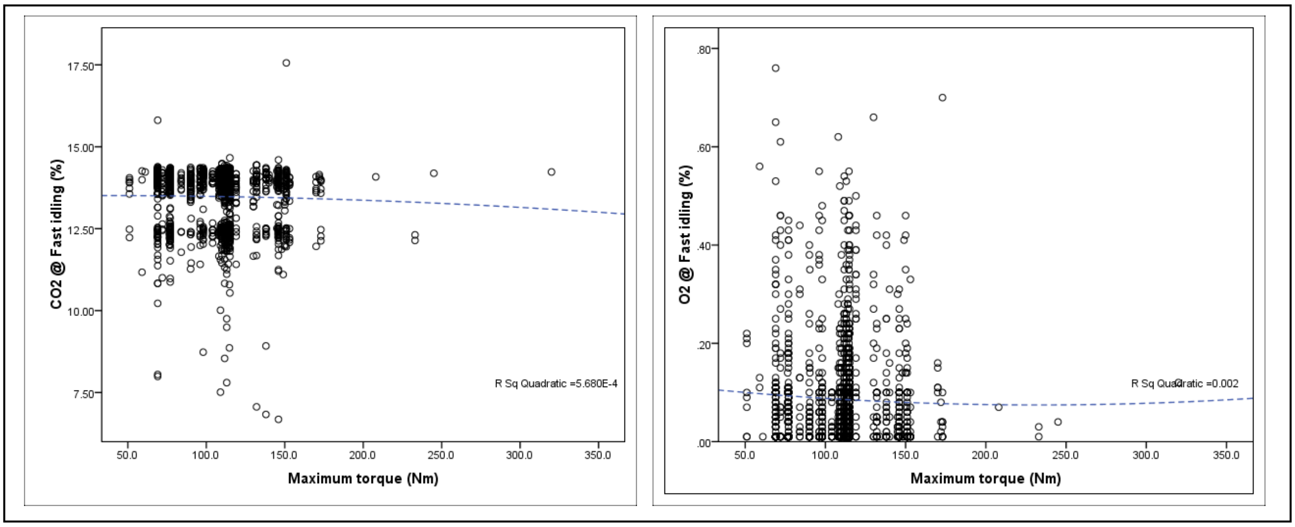


Fig. 4.135 Maximum torque vs. CO_2 and O_2 emissions (at fast idling)

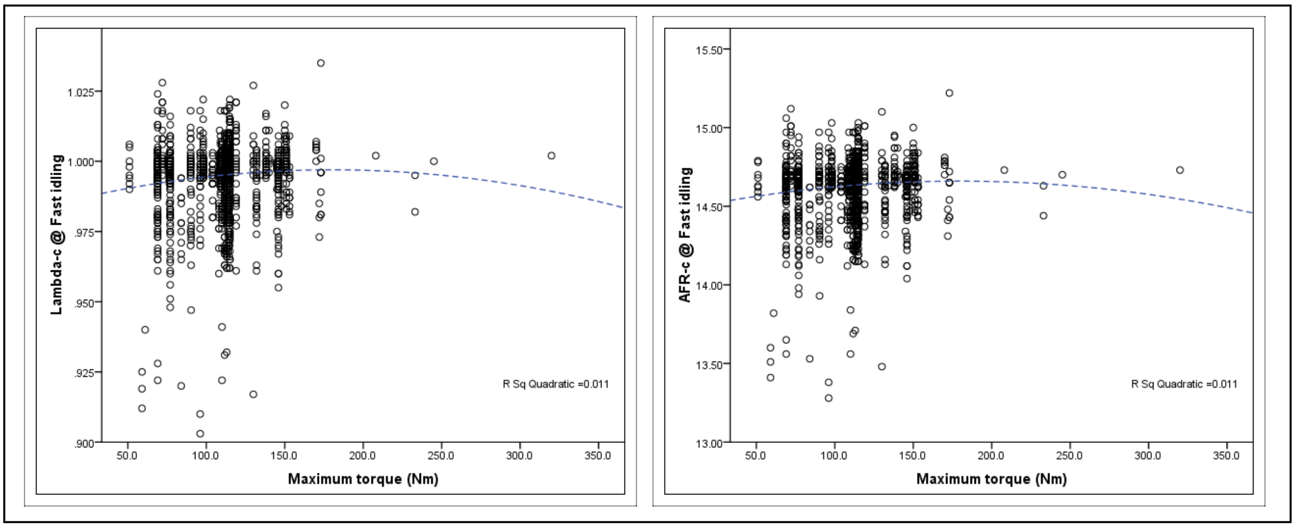


Fig. 4.136 Maximum torque vs. λ and AFR (at fast idling)

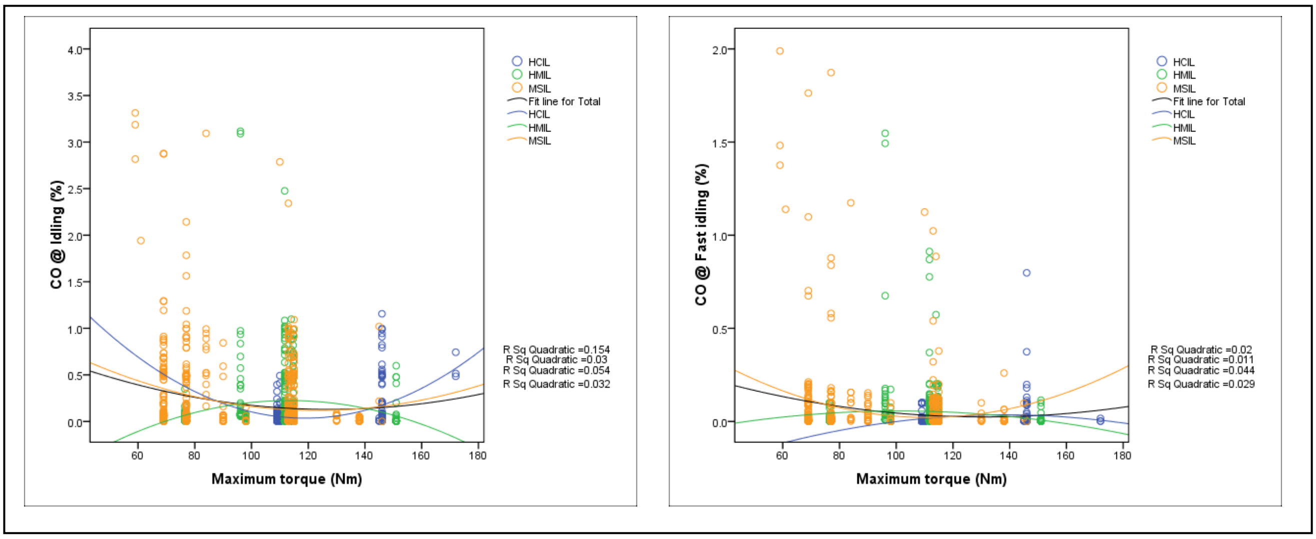


Fig. 4.137 Maximum torque vs. CO emission - top 3 makes (at idling and fast idling)

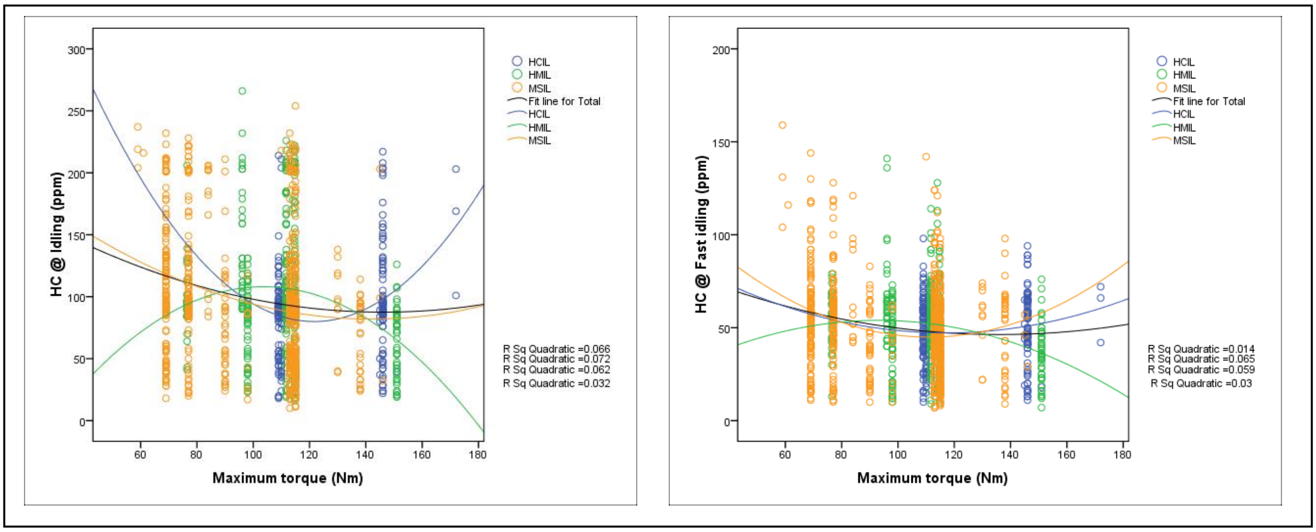


Fig. 4.138 Maximum torque vs. HC emission - top 3 makes (at idling and fast idling)

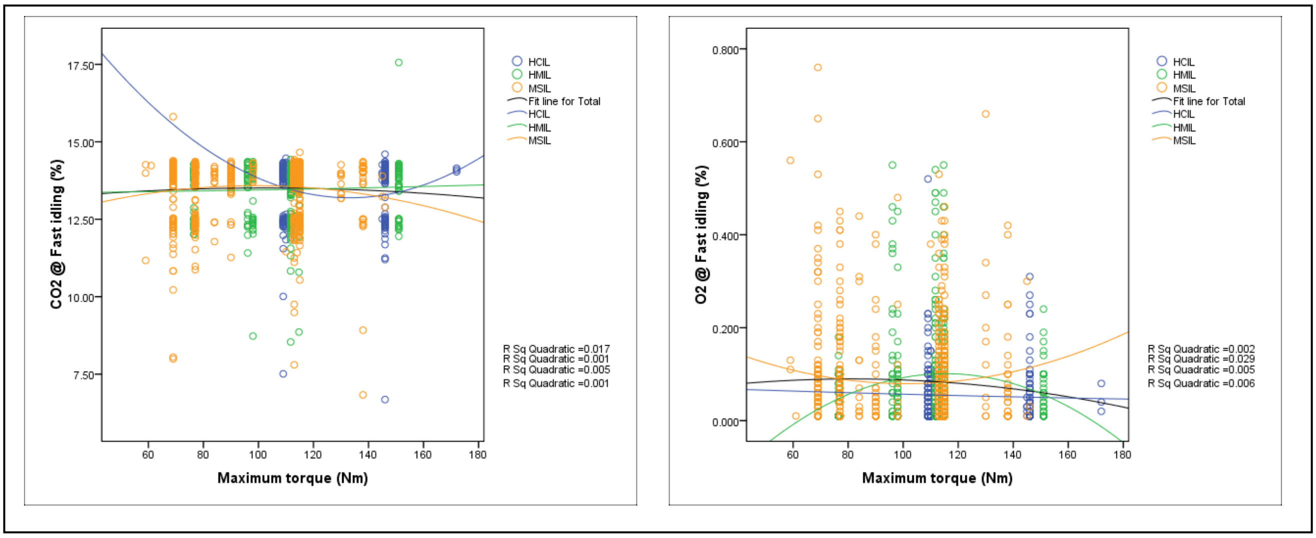


Fig. 4.139 Maximum torque vs. CO_2 and O_2 emissions - top 3 makes (at fast idling)

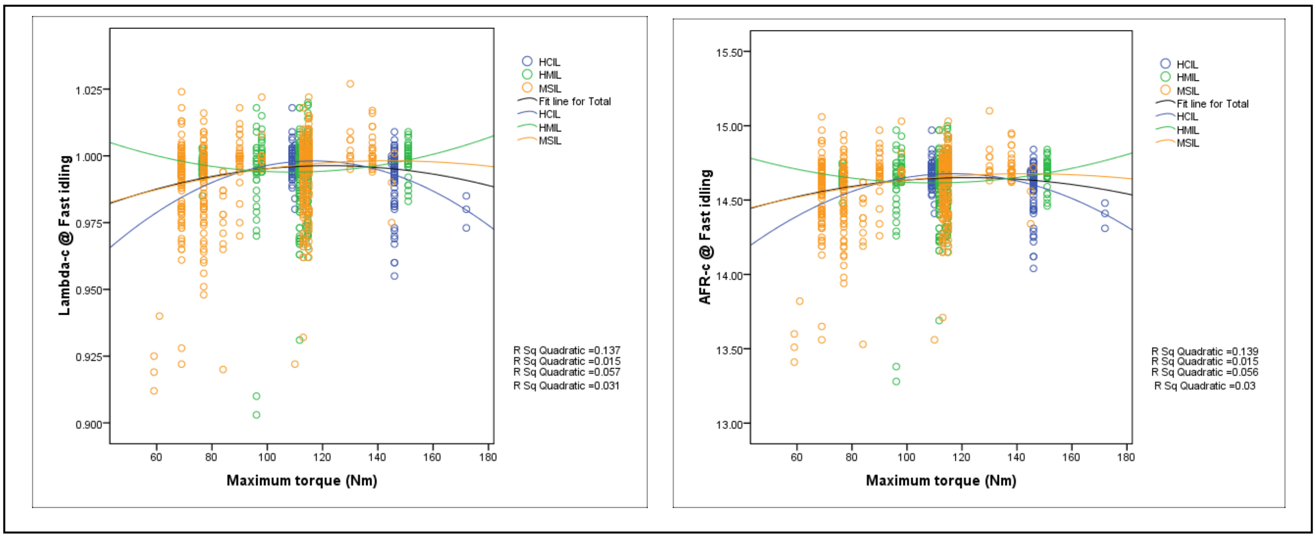


Fig. 4.140 Maximum torque vs. λ and AFR - top 3 makes (at fast idling)

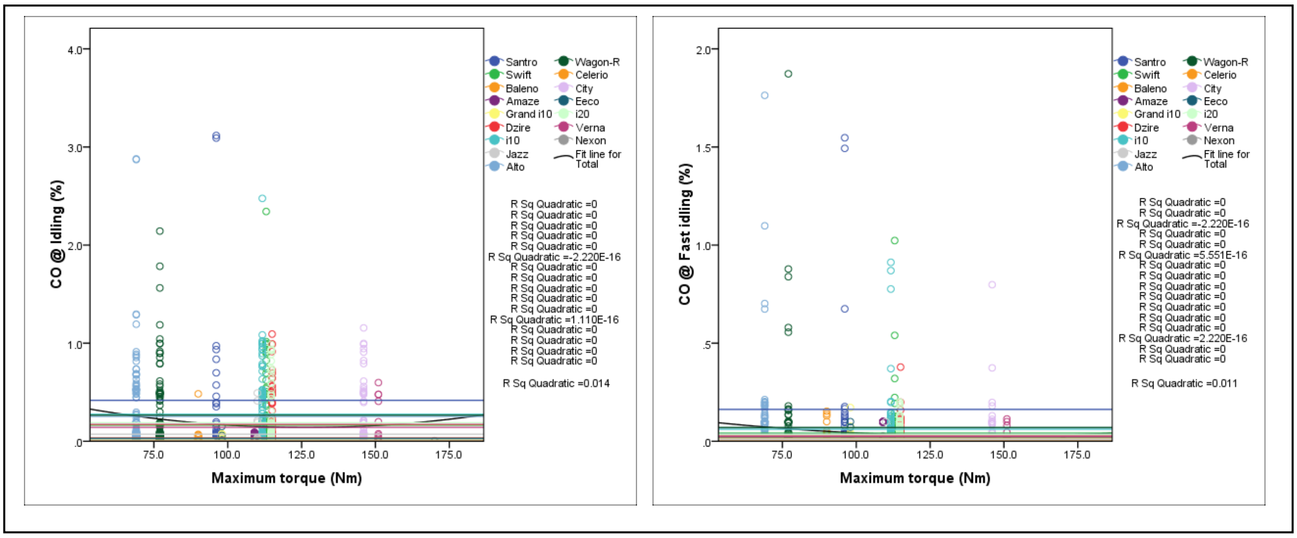


Fig. 4.141 Maximum torque vs. CO emission - top 16 models (at idling and fast idling)

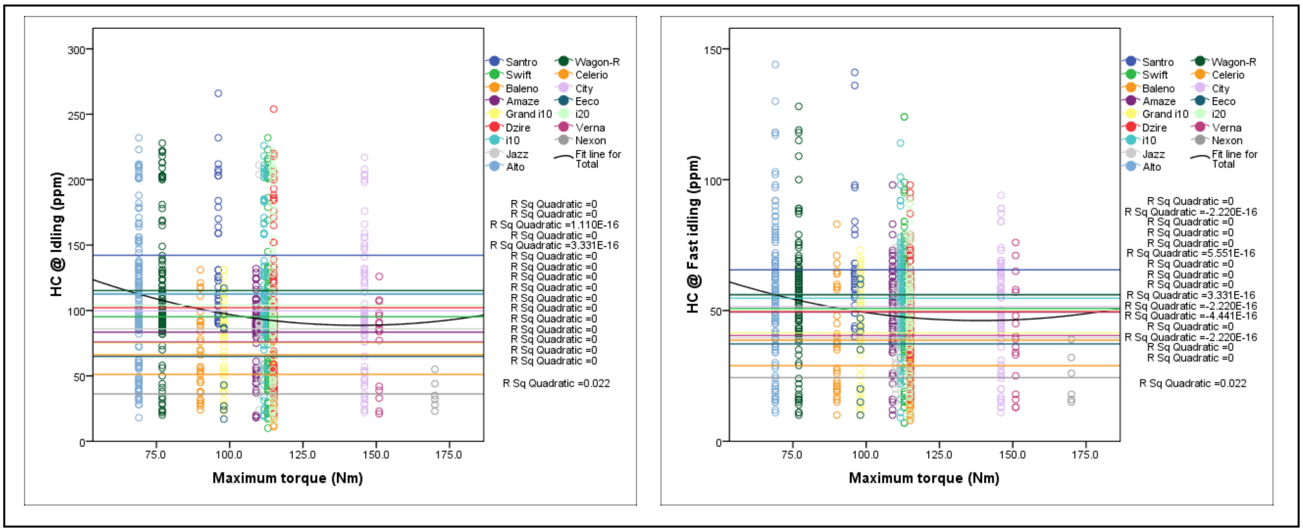


Fig. 4.142 Maximum torque vs. HC emission - top 16 models (at idling and fast idling)

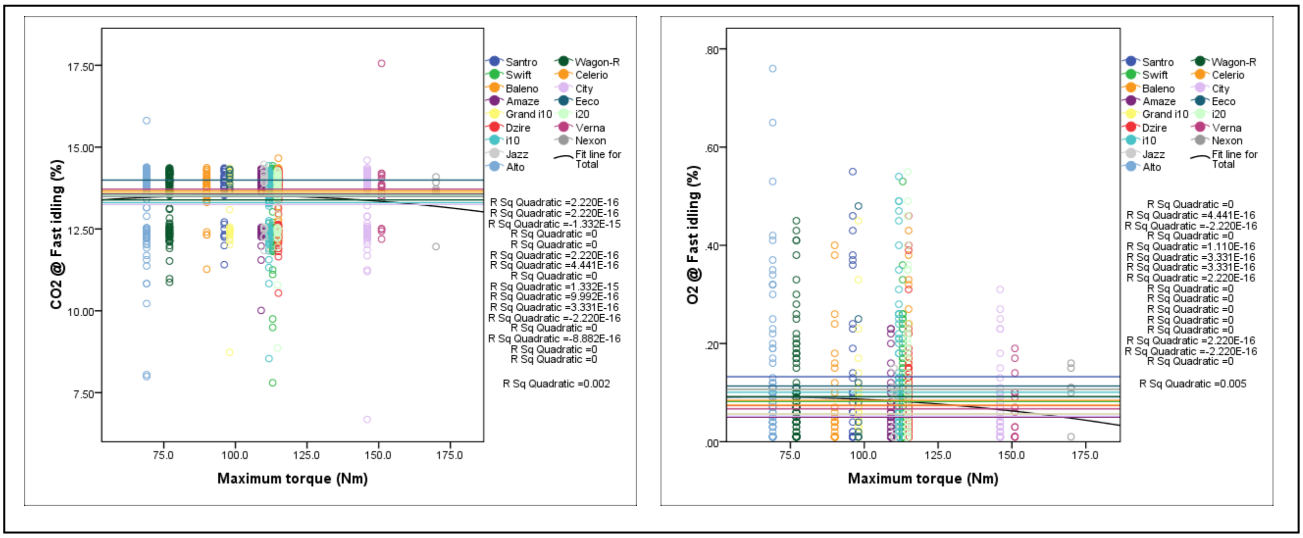


Fig. 4.143 Maximum torque vs. CO_2 and O_2 emission - top 16 models (at fast idling)

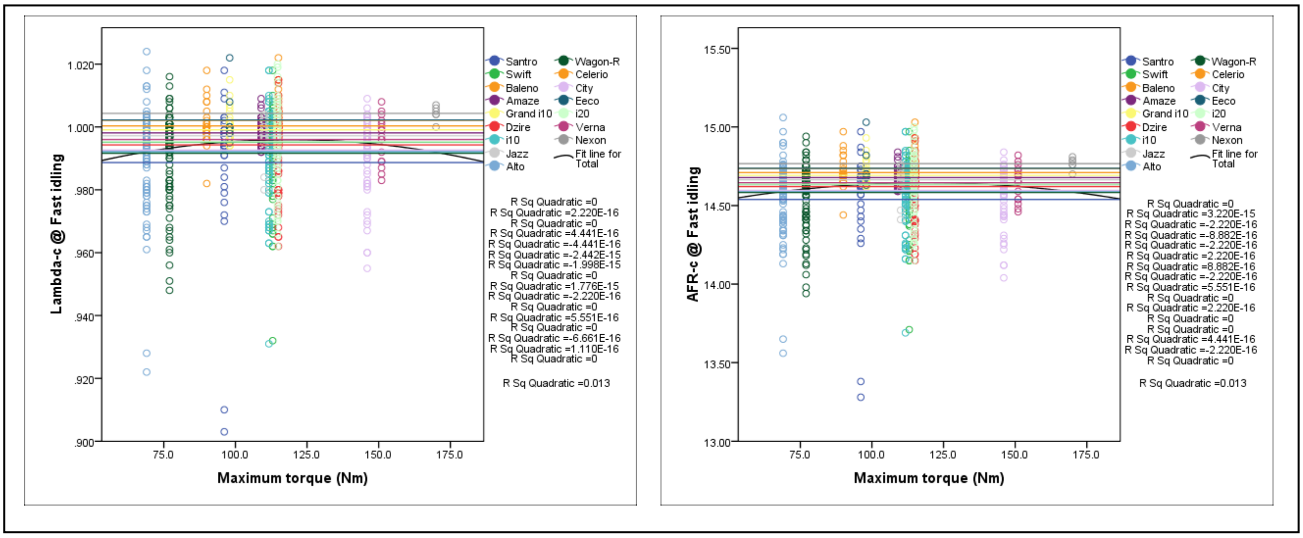


Fig. 4.144 Maximum torque vs. λ and AFR - top 16 models (at fast idling)

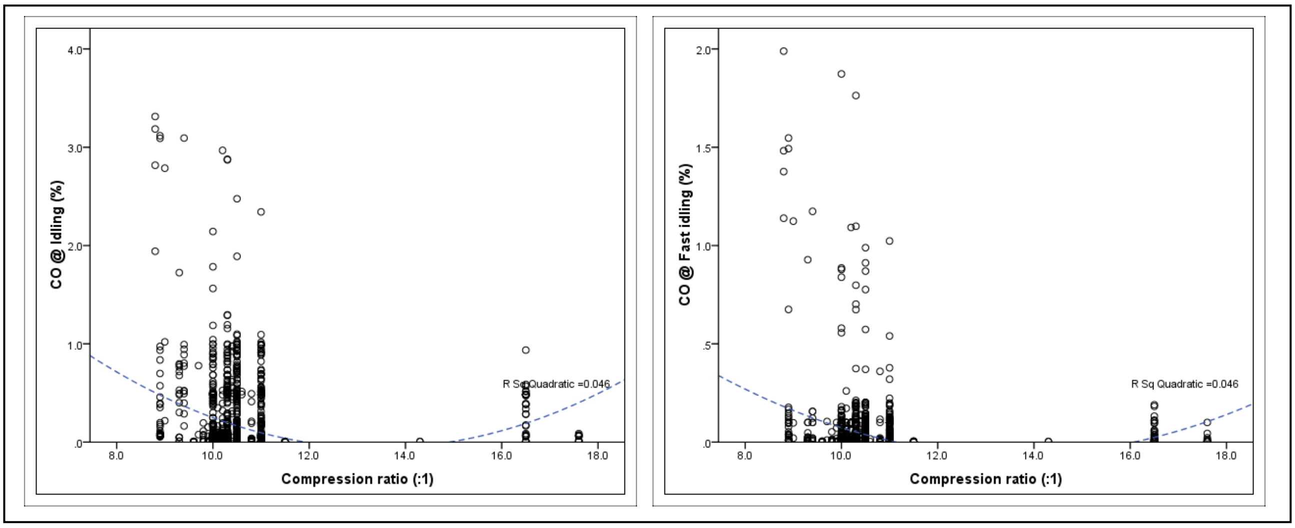


Fig. 4.145 Compression ratio vs. CO emission (at idling and fast idling)

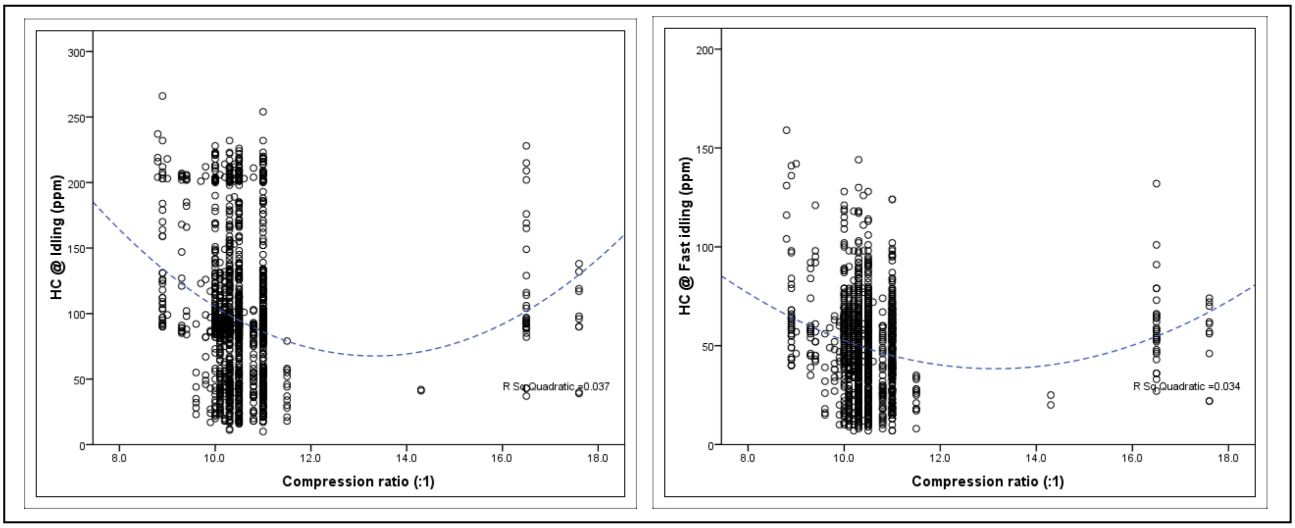


Fig. 4.146 Compression ratio vs. HC emission (at idling and fast idling)

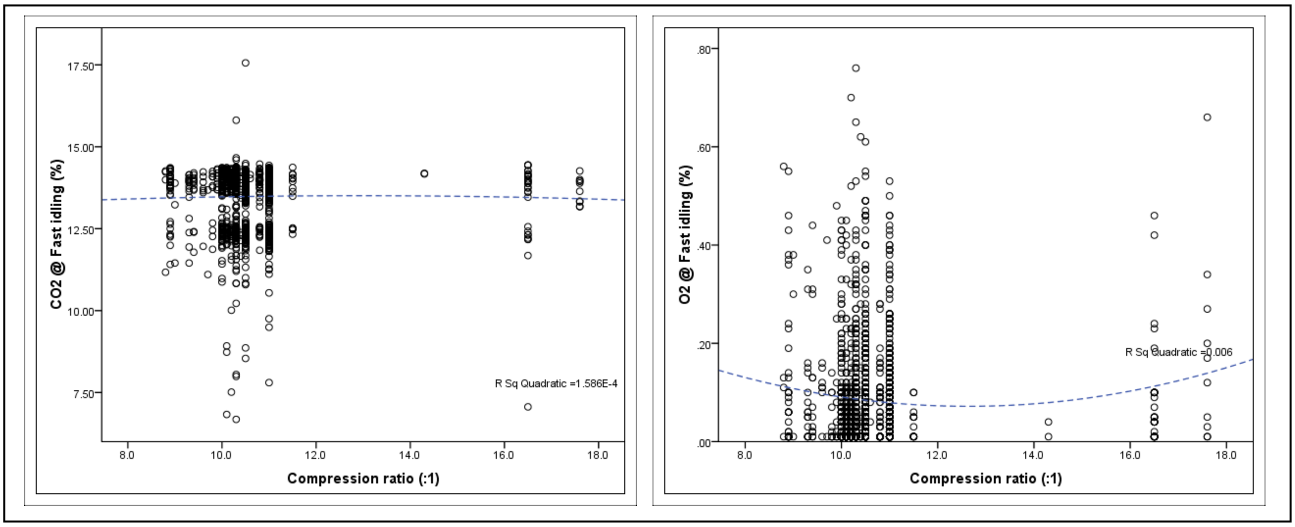


Fig. 4.147 Compression ratio vs. CO_2 and O_2 emissions (at fast idling)

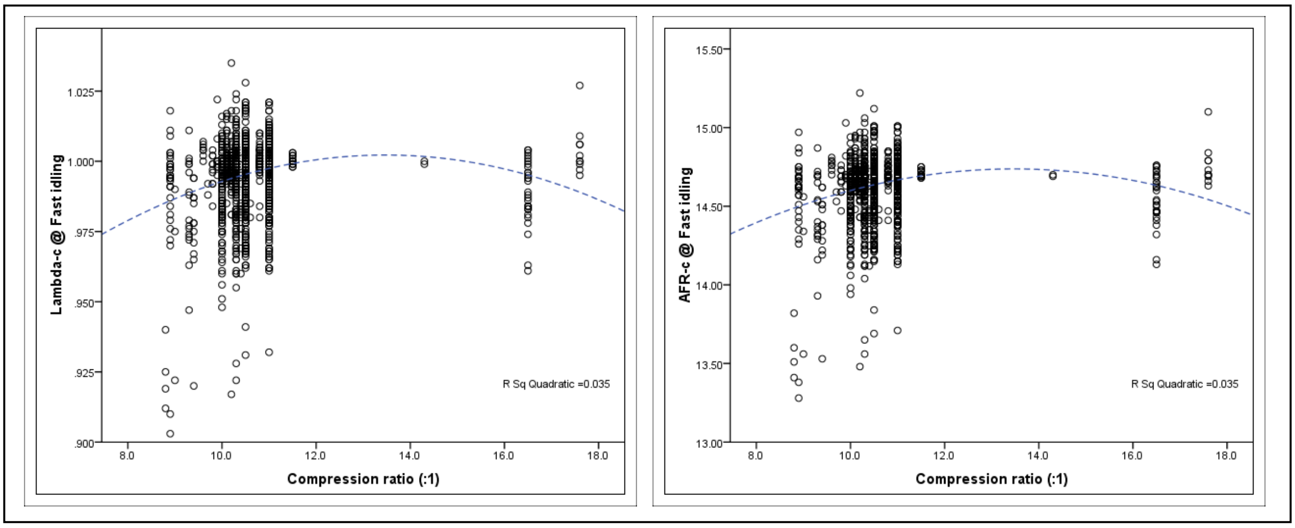


Fig. 4.148 Compression ratio vs. λ and AFR (at fast idling)

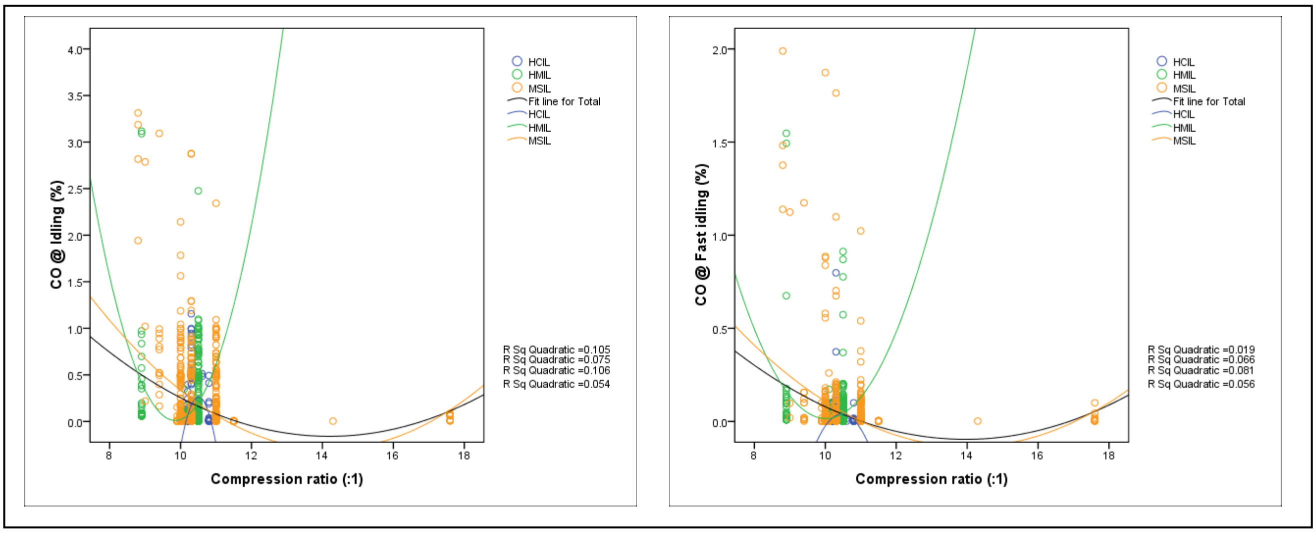


Fig. 4.149 Compression ratio vs. CO emission - top 3 makes (at idling and fast idling)

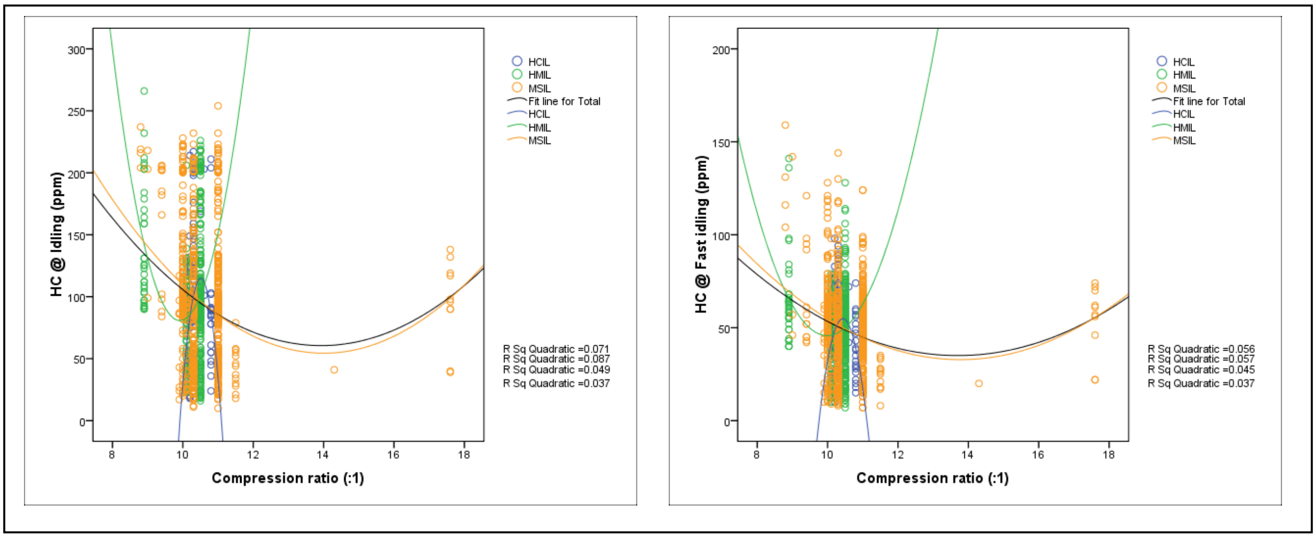


Fig. 4.150 Compression ratio vs. HC emission - top 3 makes (at idling and fast idling)

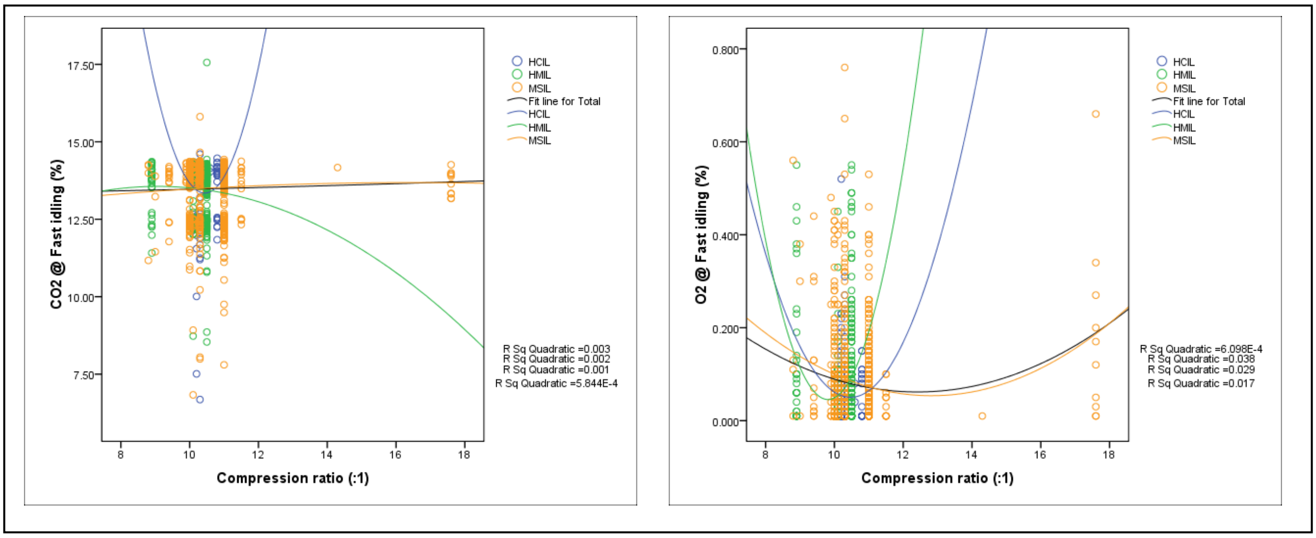


Fig. 4.151 Compression ratio vs. CO_2 and O_2 emissions - top 3 makes (at fast idling)

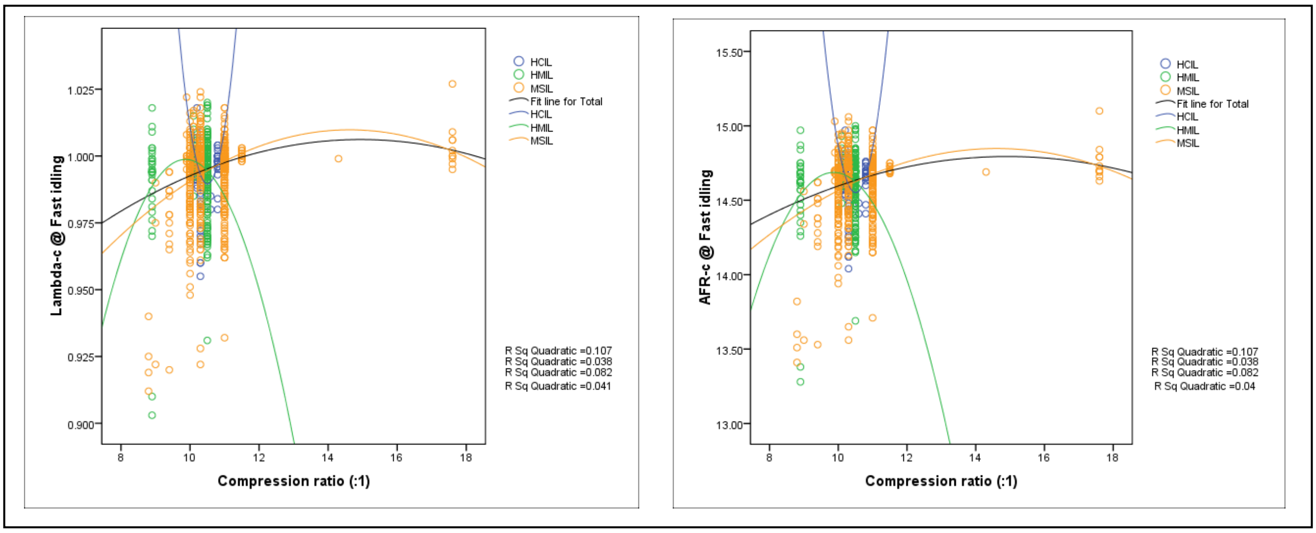


Fig. 4.152 Compression ratio vs. λ and AFR - top 3 makes (at fast idling)

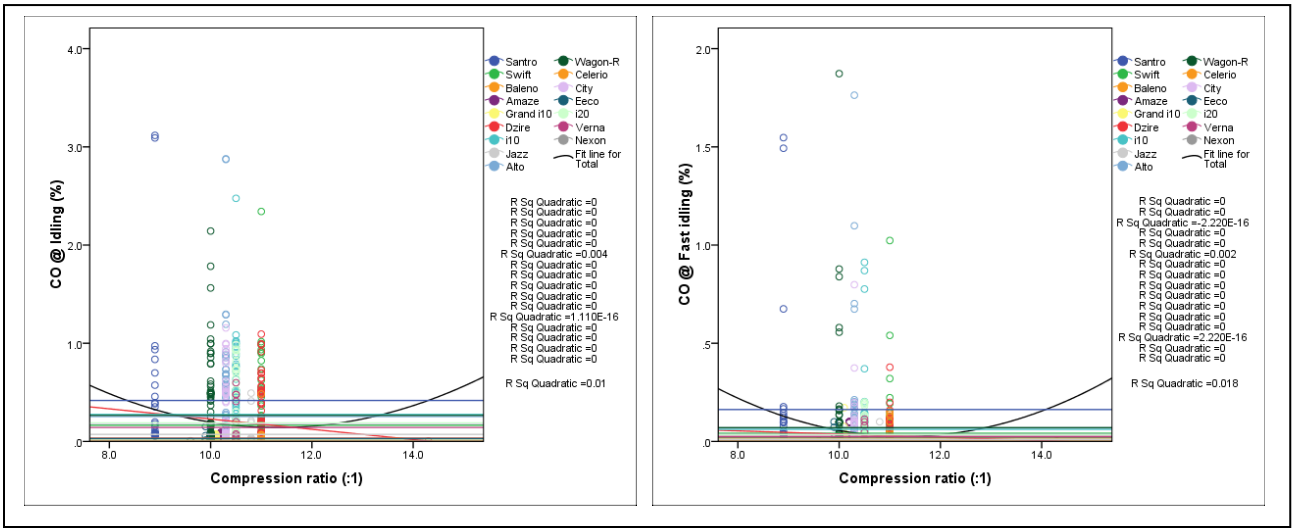


Fig. 4.153 Compression ratio vs. CO emission - top 16 models (at idling and fast idling)

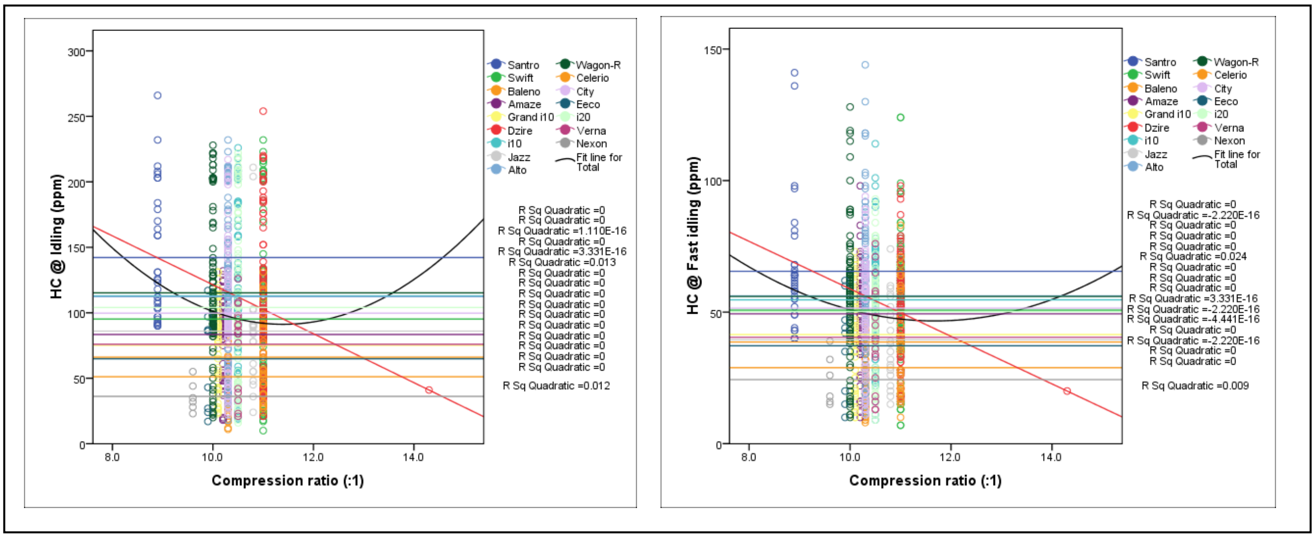


Fig. 4.154 Compression ratio vs. HC emission - top 16 models (at idling and fast idling)

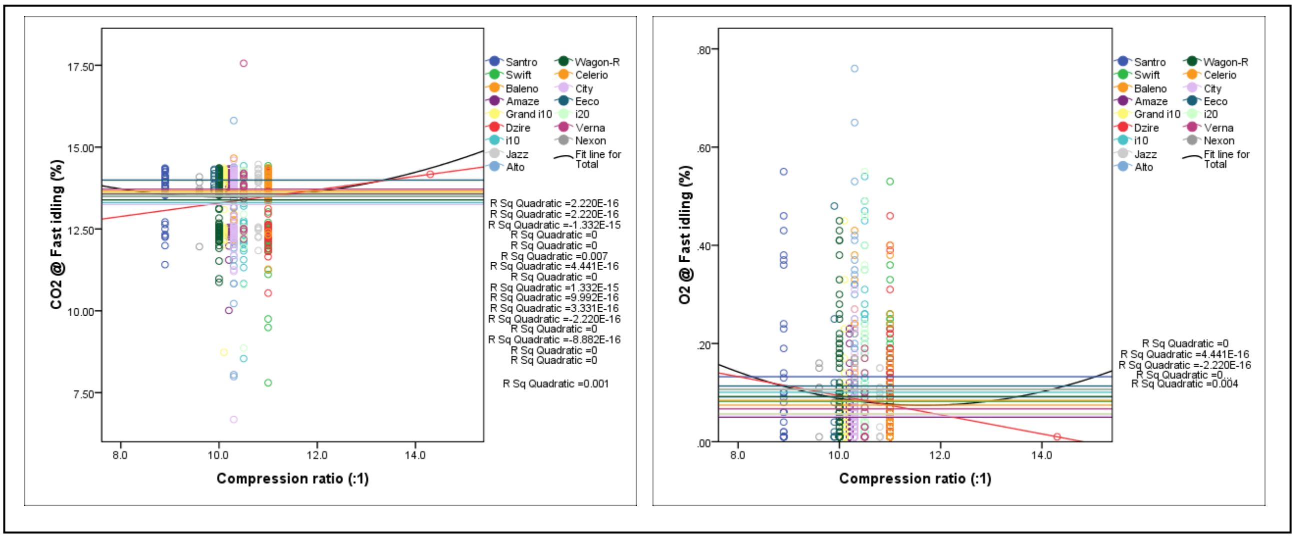


Fig. 4.155 Compression ratio vs. CO₂ and O₂ emission - top 16 models (at fast idling)

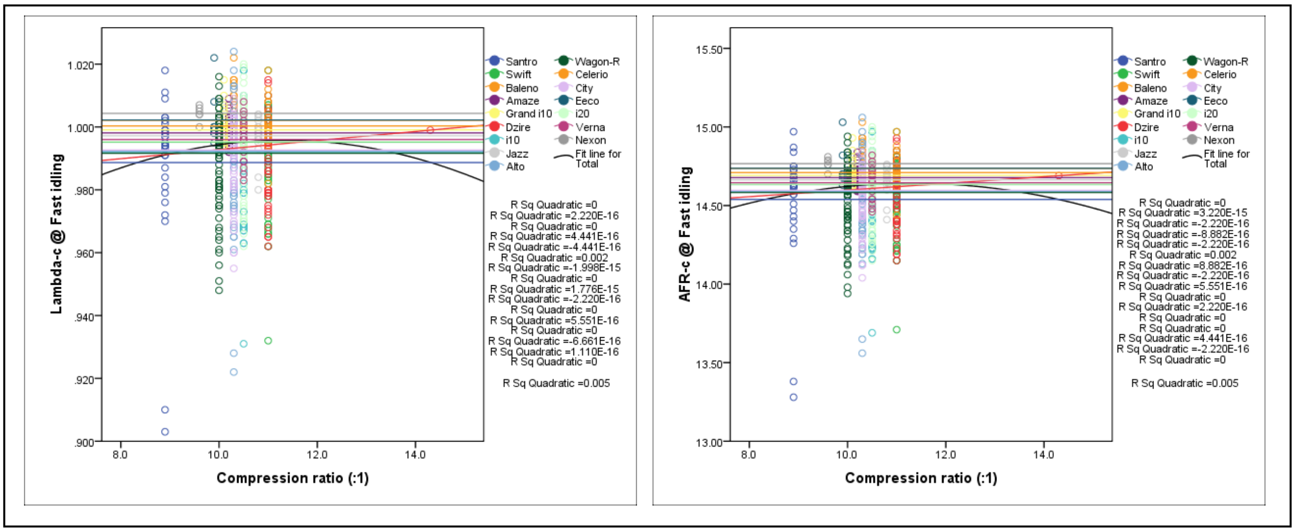


Fig. 4.156 Compression ratio vs. λ and AFR - top 16 models (at fast idling)

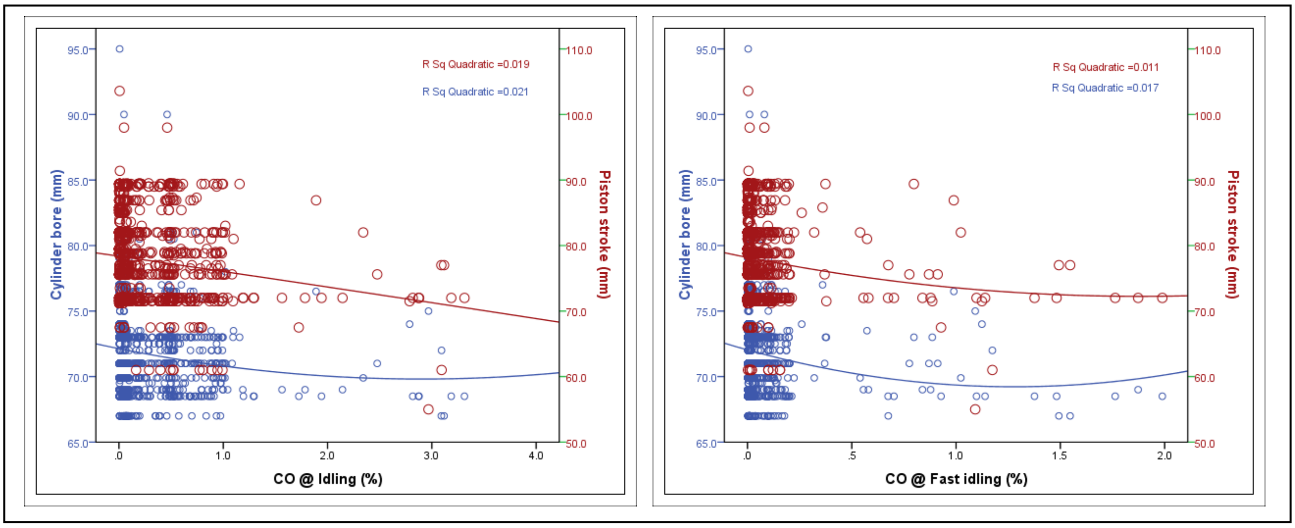


Fig. 4.157 Bore and stroke vs. CO emission (at idling and fast idling)

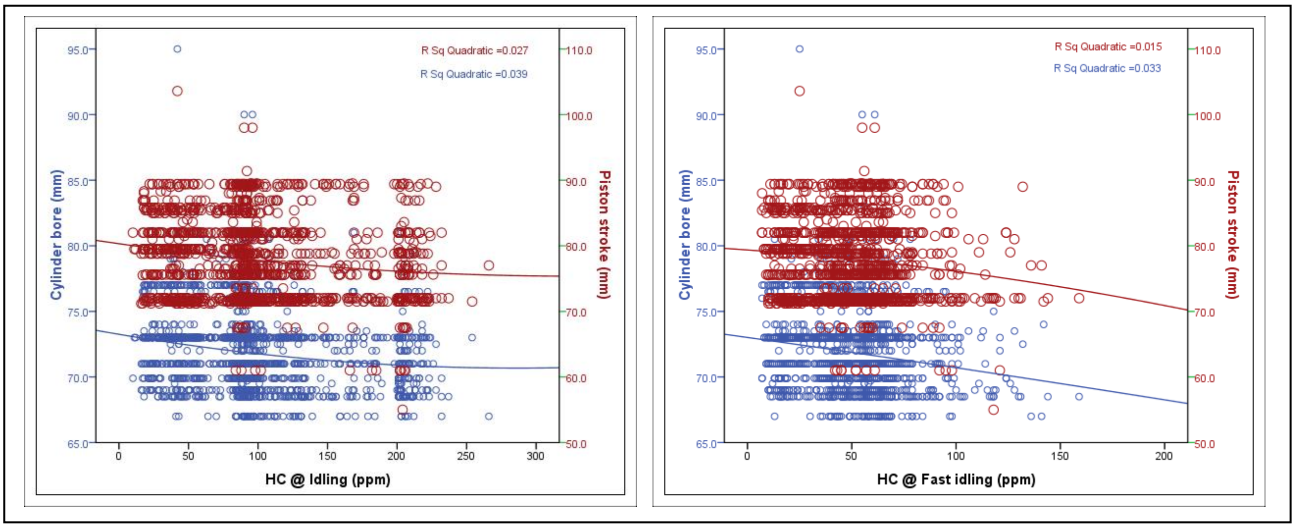


Fig. 4.158 Bore and stroke vs. HC emission (at idling and fast idling)

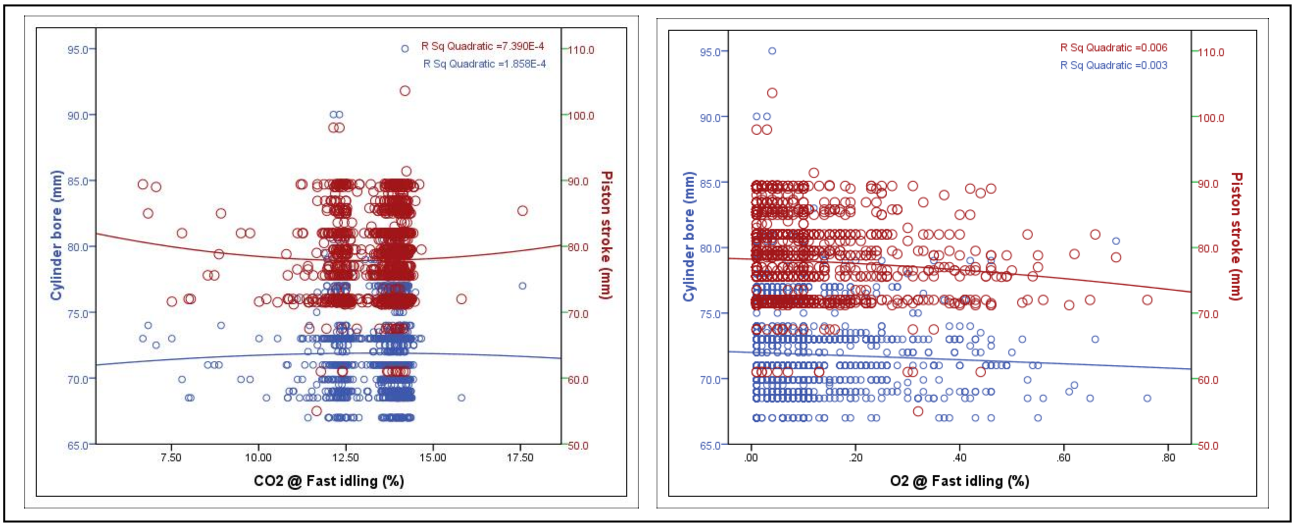


Fig. 4.159 Bore and stroke vs. CO_2 and O_2 emissions (at fast idling)

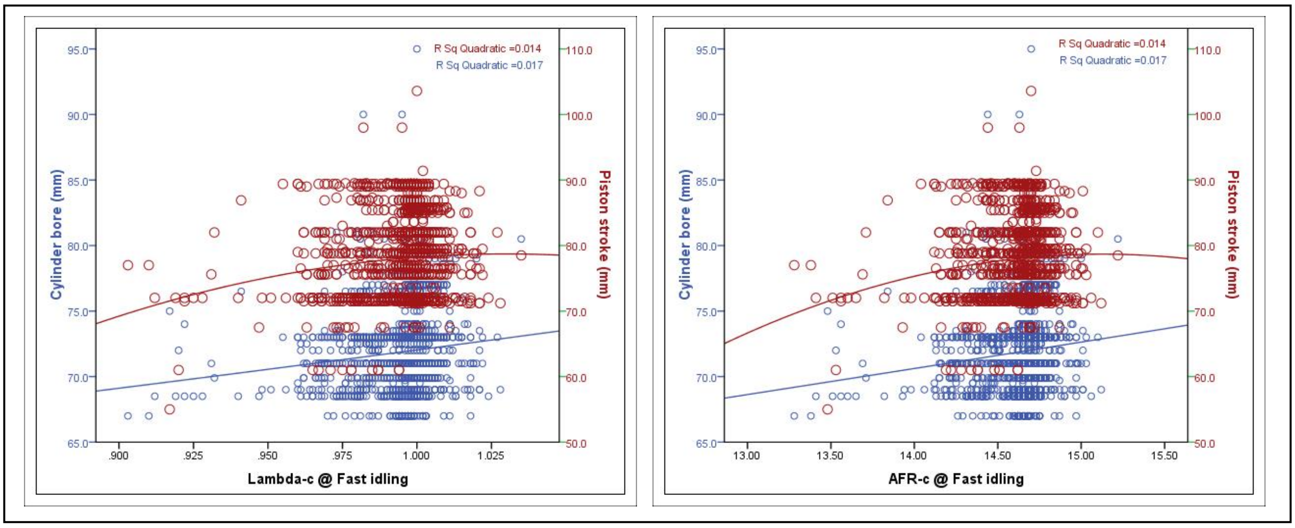


Fig. 4.160 Bore and stroke vs. λ and AFR (at fast idling)

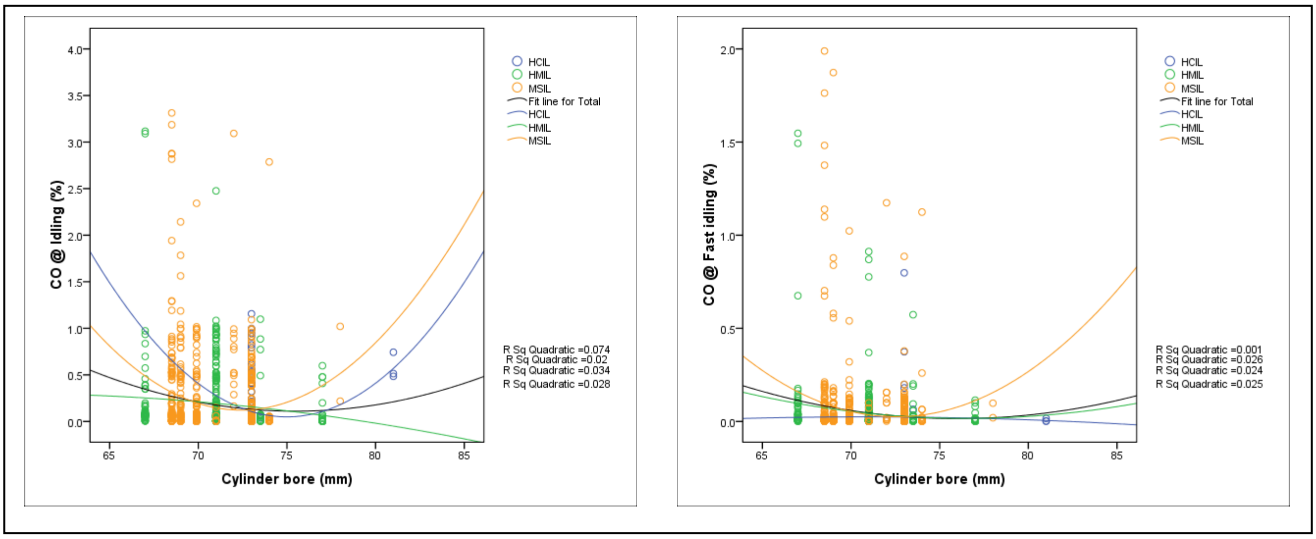


Fig. 4.161 Cylinder bore vs. CO emission - top 3 makes (at idling and fast idling)

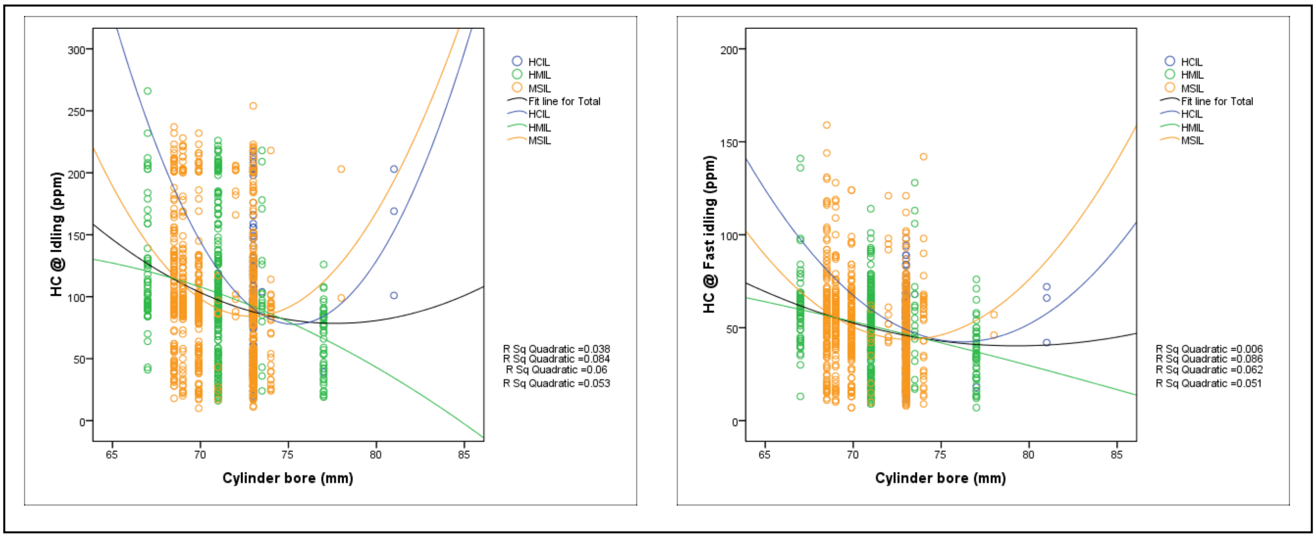


Fig. 4.162 Cylinder bore vs. HC emission - top 3 makes (at idling and fast idling)

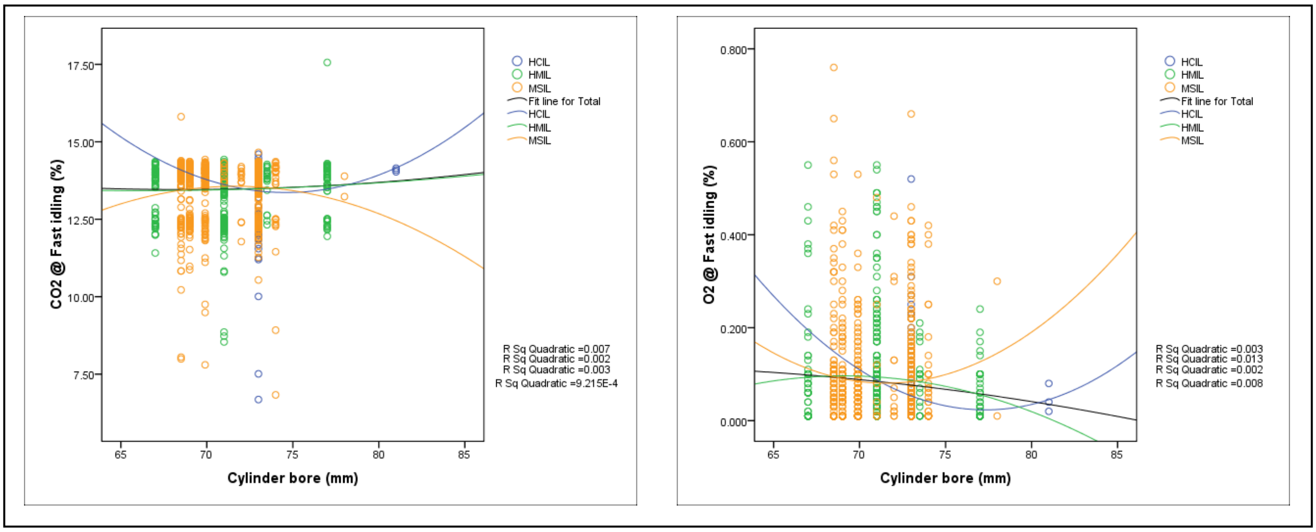


Fig. 4.163 Cylinder bore vs. CO_2 and O_2 emissions - top 3 makes (at fast idling)

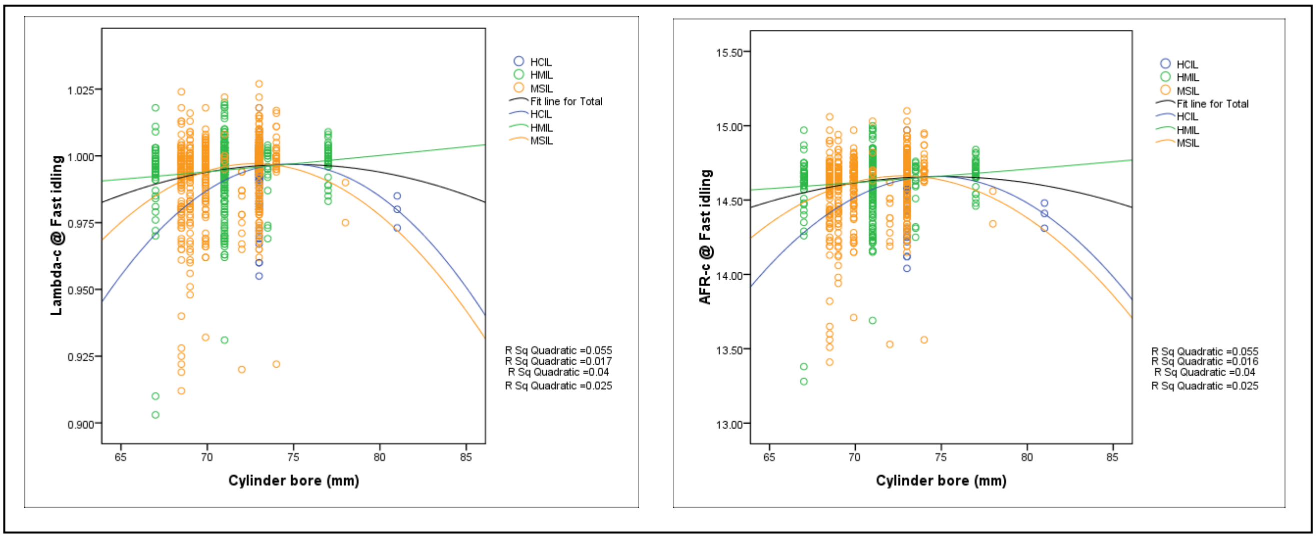


Fig. 4.164 Cylinder bore vs. λ and AFR - top 3 makes (at fast idling)

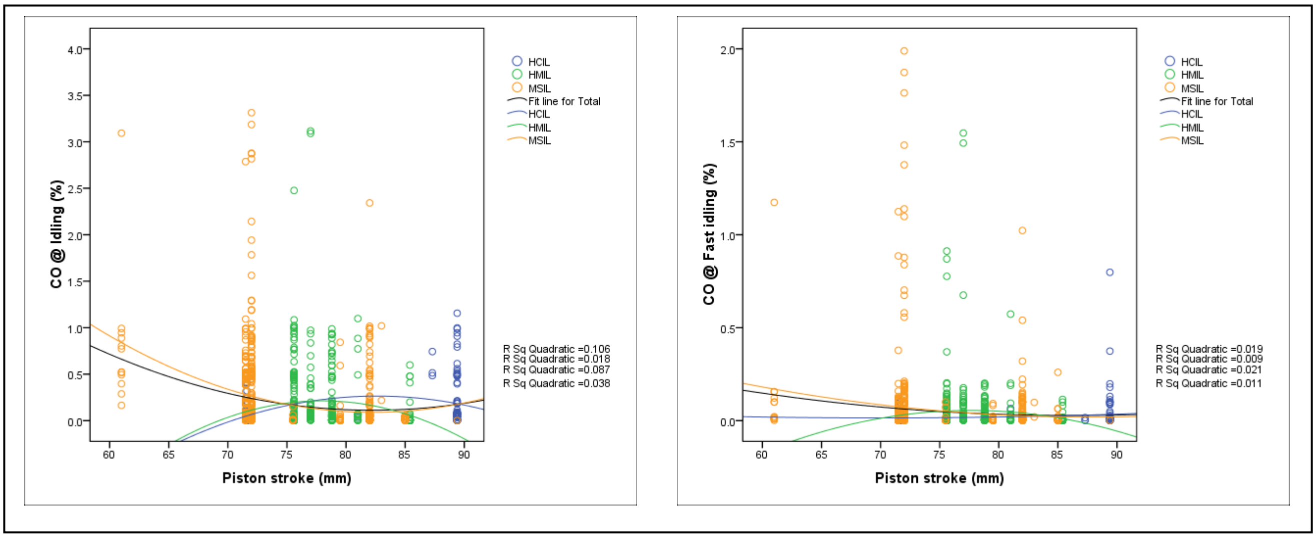


Fig. 4.165 Piston stroke vs. CO emission - top 3 makes (at idling and fast idling)

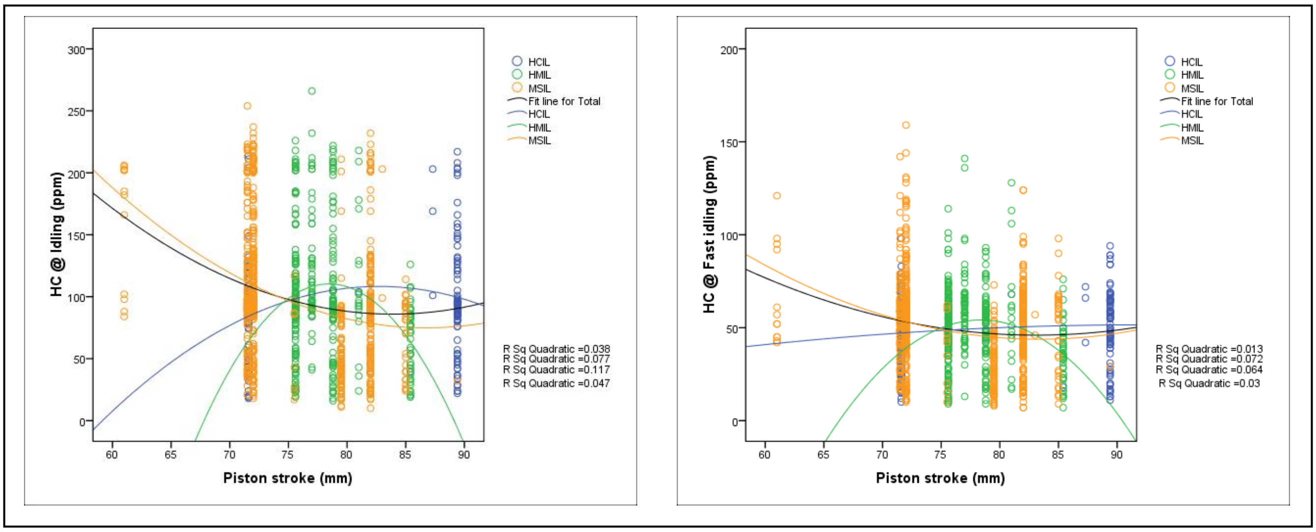


Fig. 4.166 Piston stroke vs. HC emission - top 3 makes (at idling and fast idling)

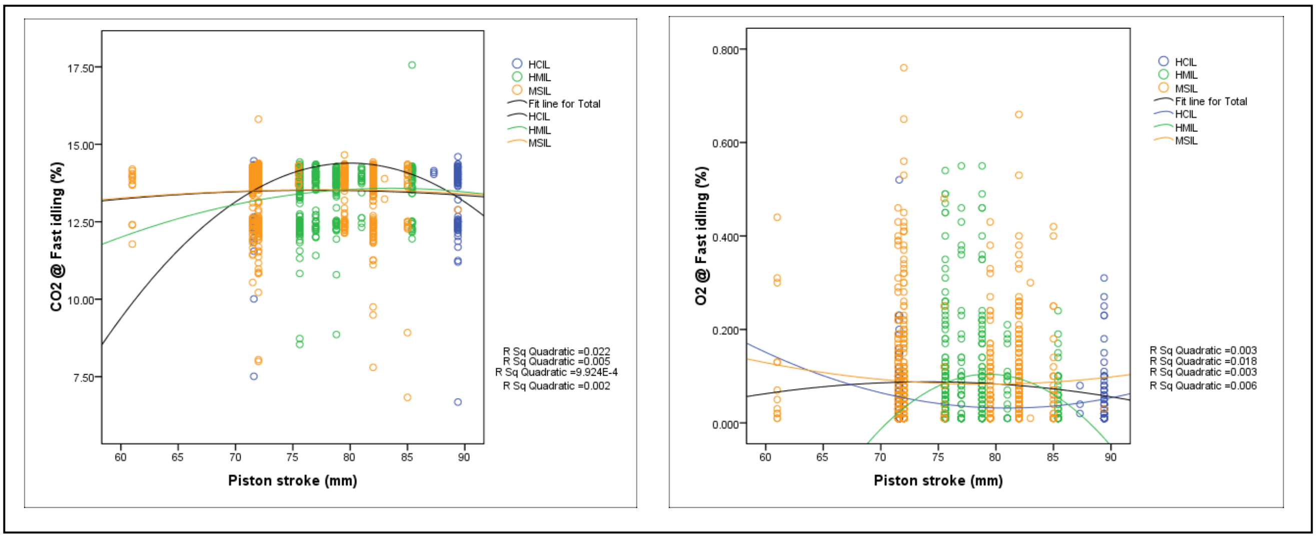


Fig. 4.167 Piston stroke vs. CO_2 and O_2 emissions - top 3 makes (at fast idling)

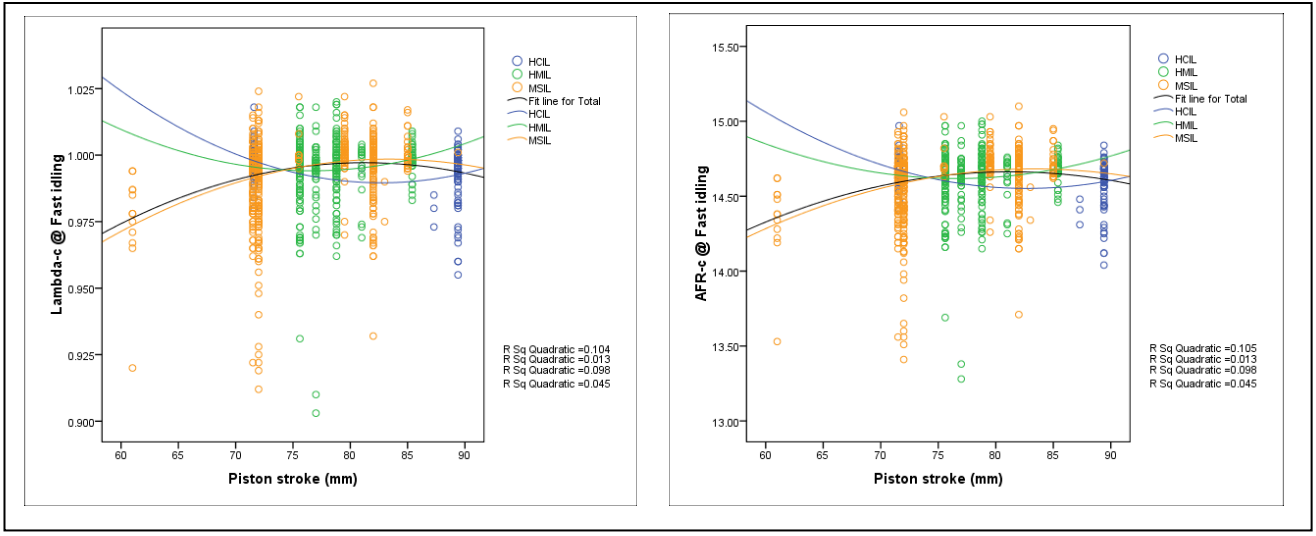


Fig. 4.168 Piston stroke vs. λ and AFR - top 3 makes (at fast idling)

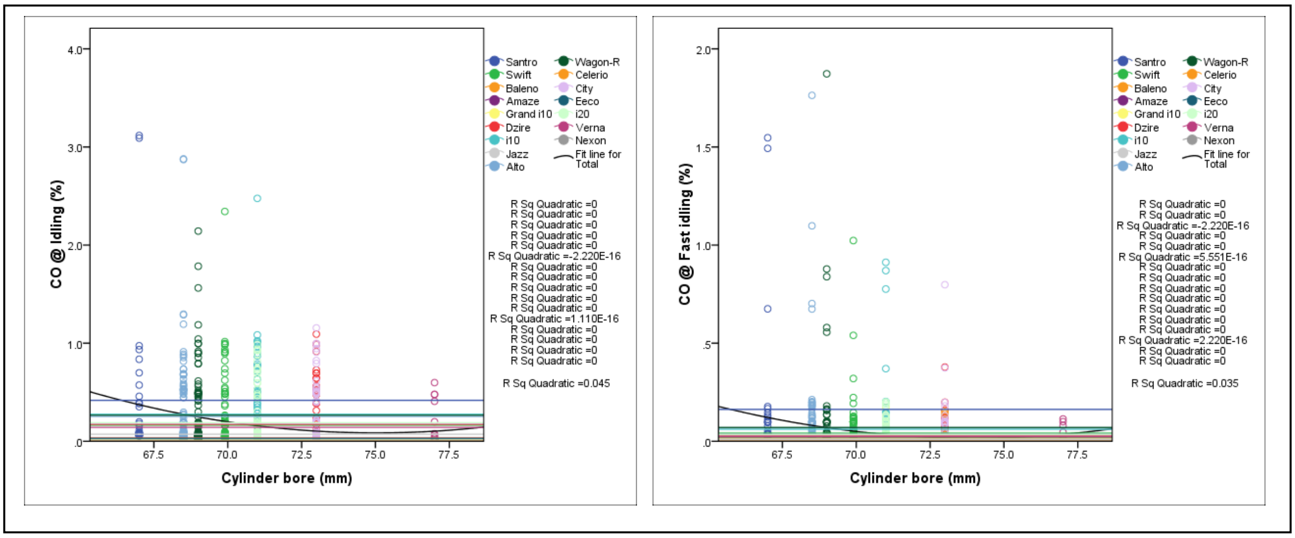


Fig. 4.169 Cylinder bore vs. CO emission - top 16 models (at idling and fast idling)

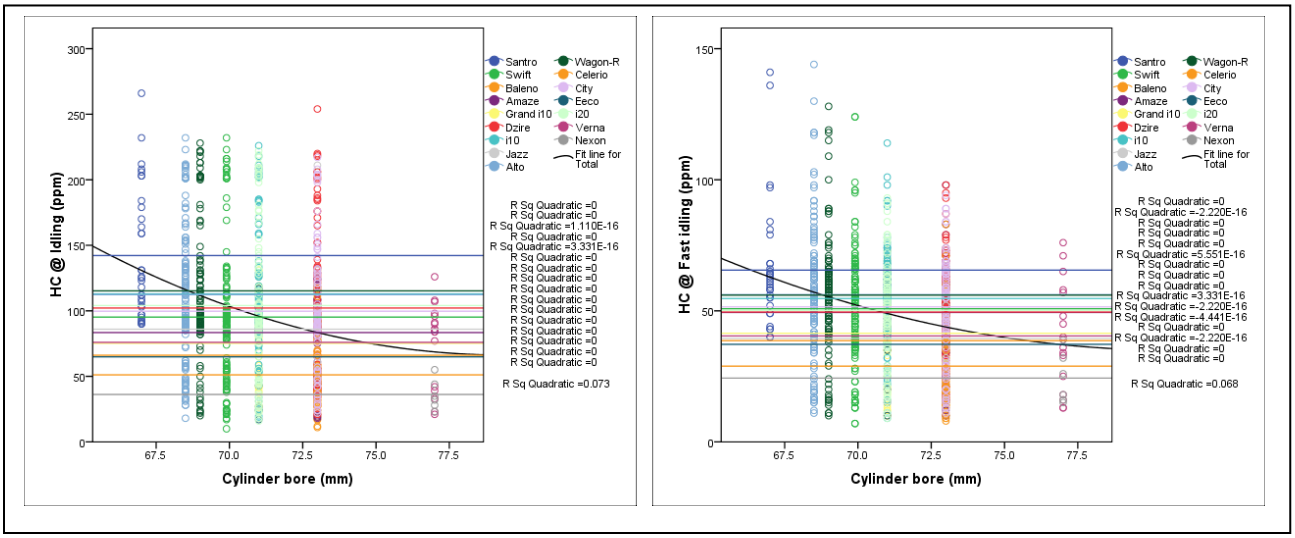


Fig. 4.170 Cylinder bore vs. HC emission - top 16 models (at idling and fast idling)

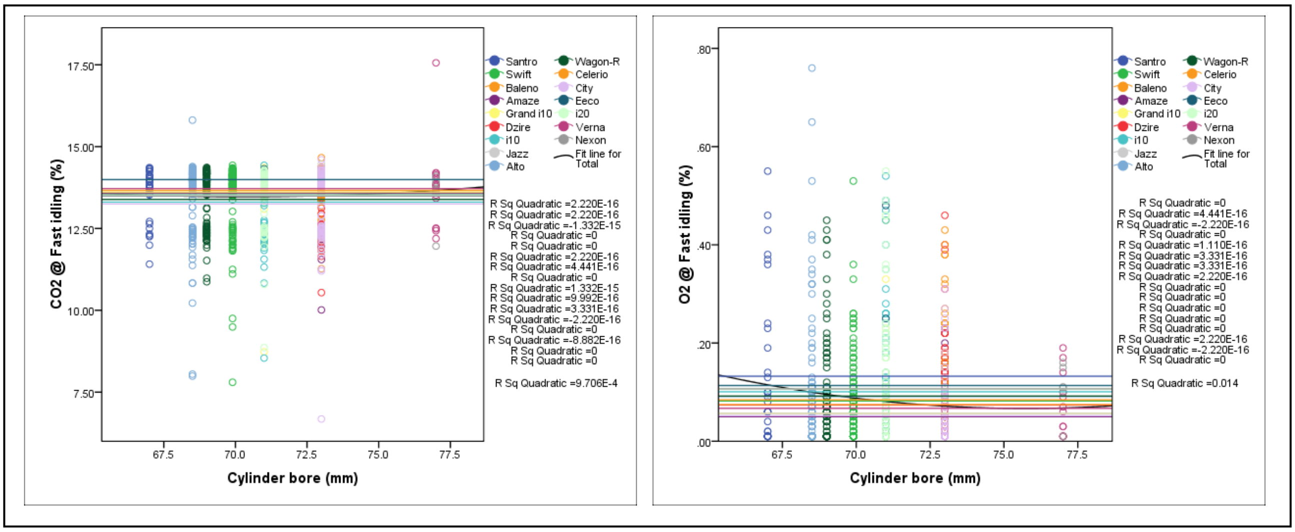


Fig. 4.171 Cylinder bore vs. CO_2 and O_2 emission - top 16 models (at fast idling)

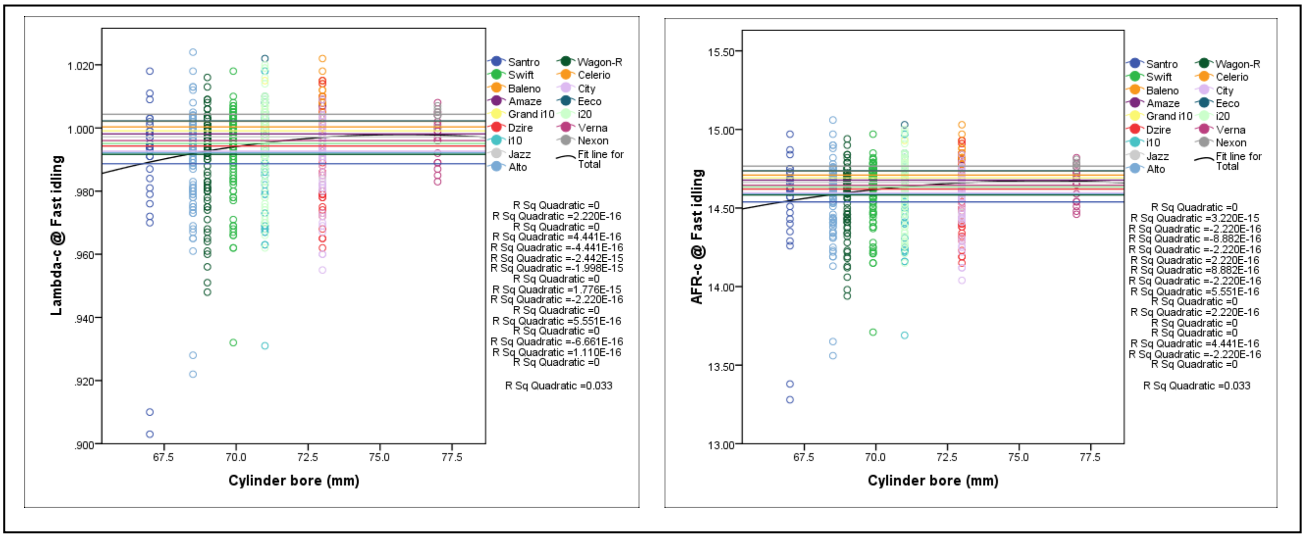


Fig. 4.172 Cylinder bore vs. λ and AFR - top 16 models (at fast idling)

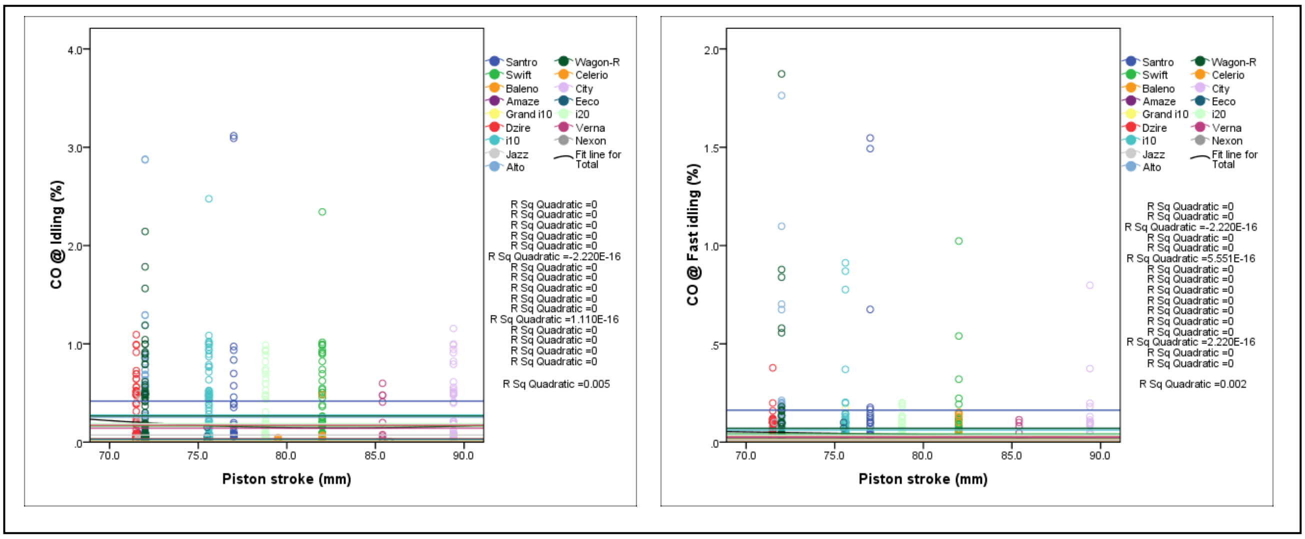


Fig. 4.173 Piston stroke vs. CO emission - top 16 models (at idling and fast idling)

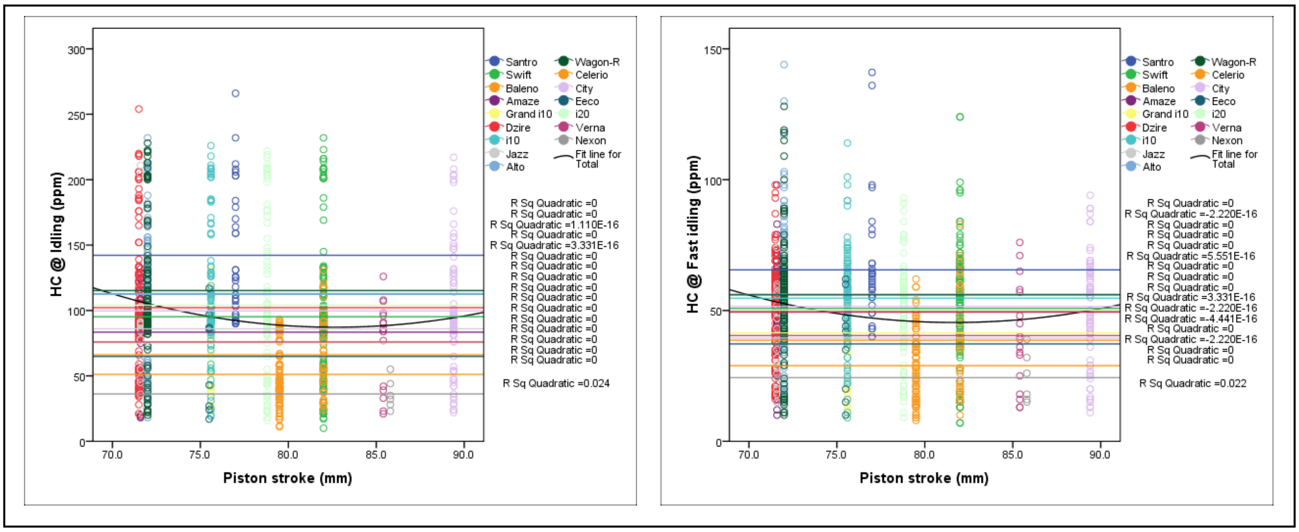


Fig. 4.174 Piston stroke vs. HC emission - top 16 models (at idling and fast idling)

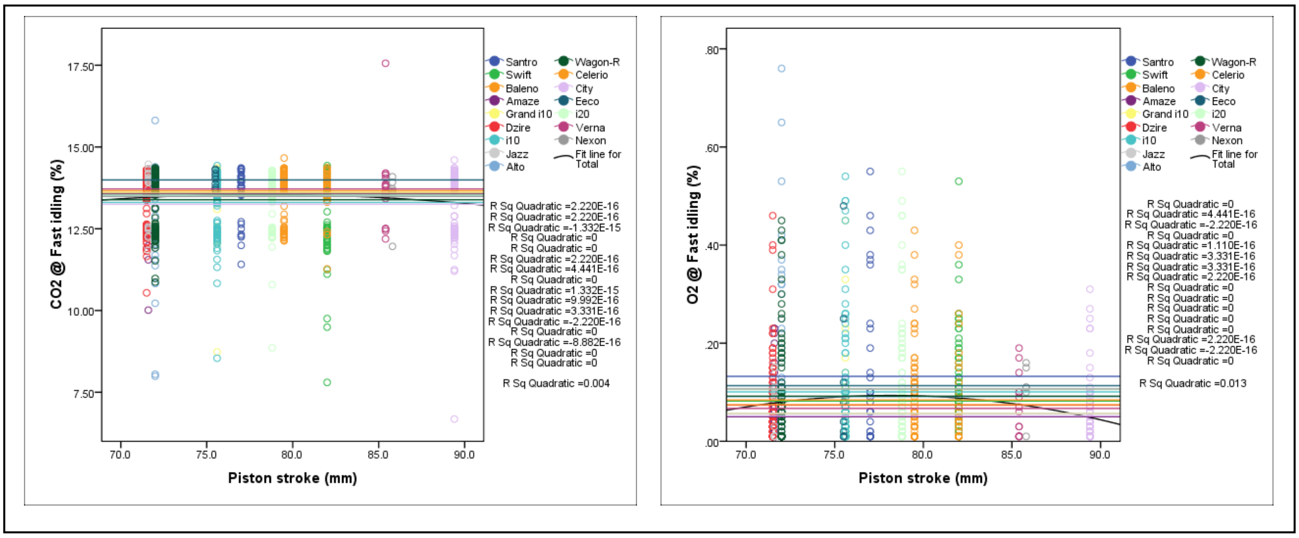


Fig. 4.175 Piston stroke vs. CO_2 and O_2 emission - top 16 models (at fast idling)

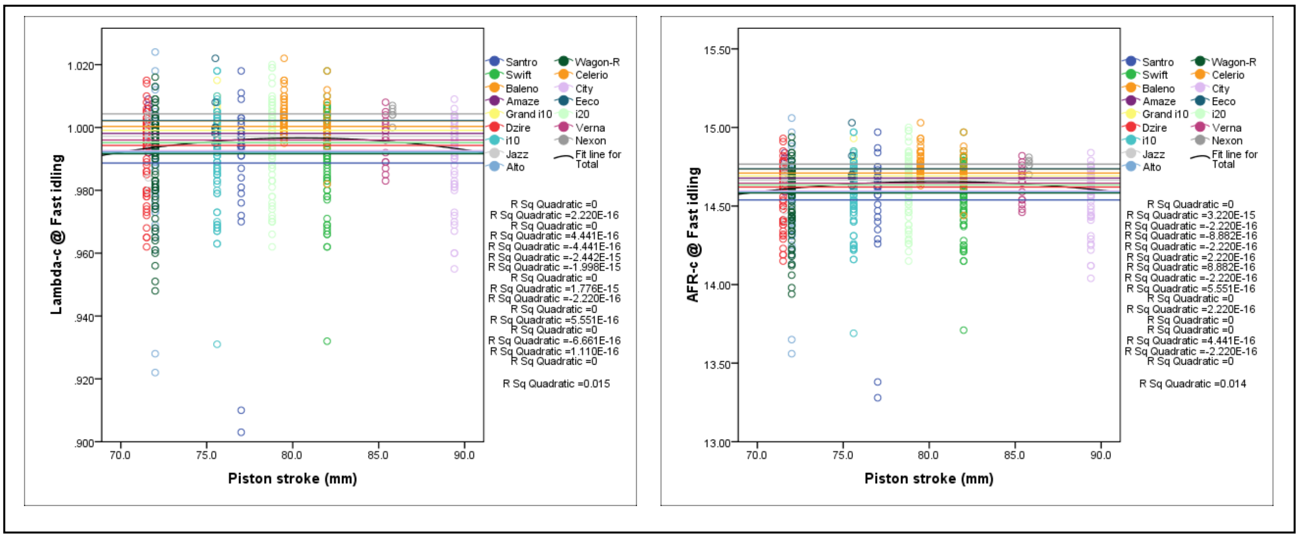


Fig. 4.176 Piston stroke vs. λ and AFR - top 16 models (at fast idling)

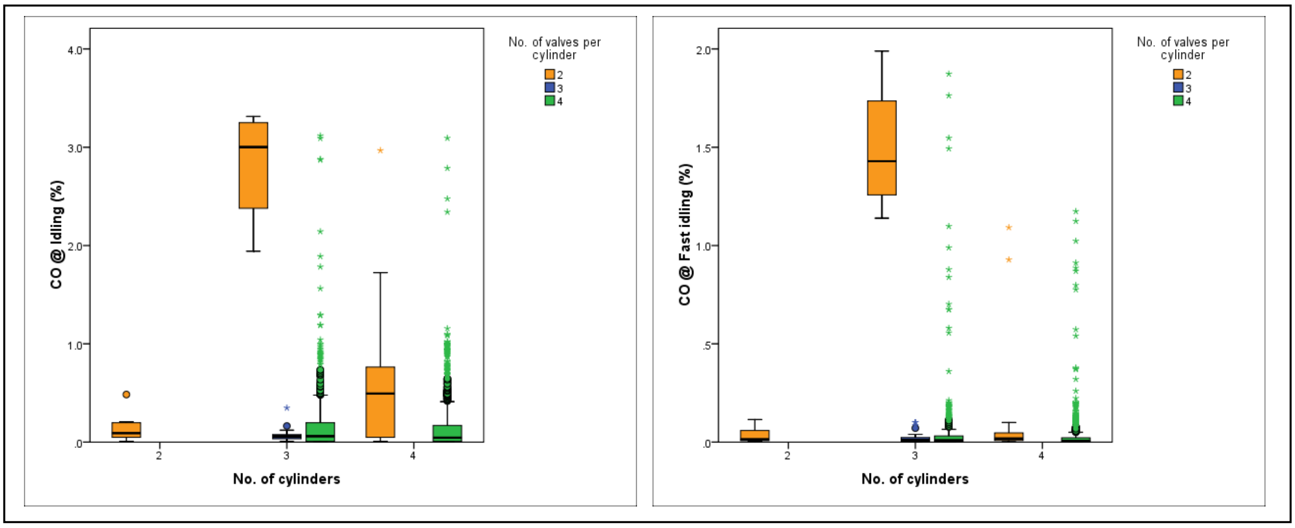


Fig. 4.177 No. of cylinders / valves vs. CO emission (at idling and fast idling)

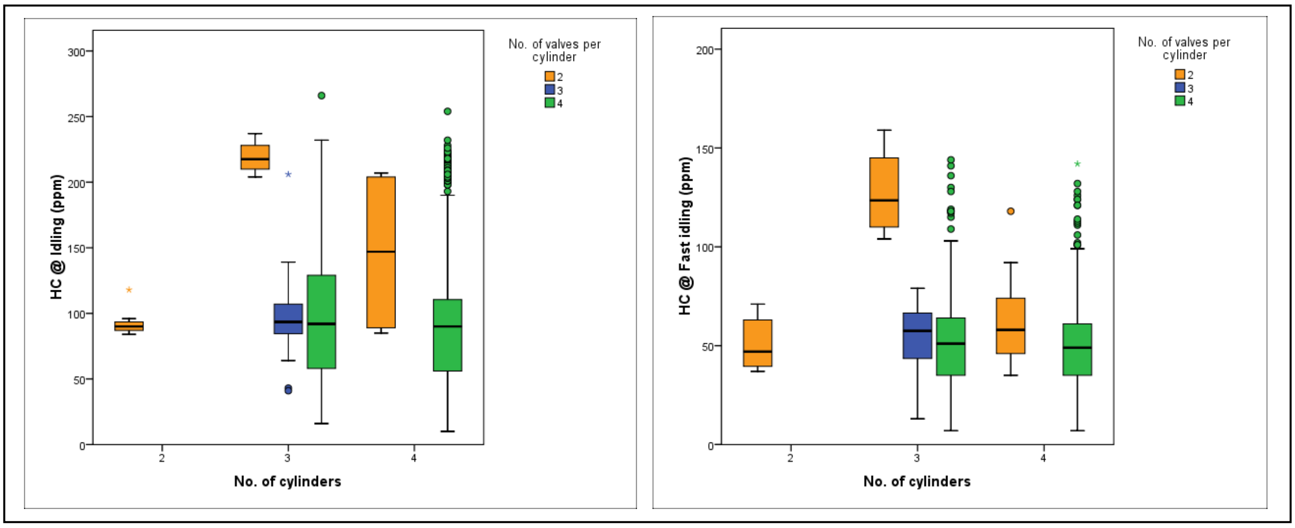


Fig. 4.178 No. of cylinders / valves vs. HC emission (at idling and fast idling)

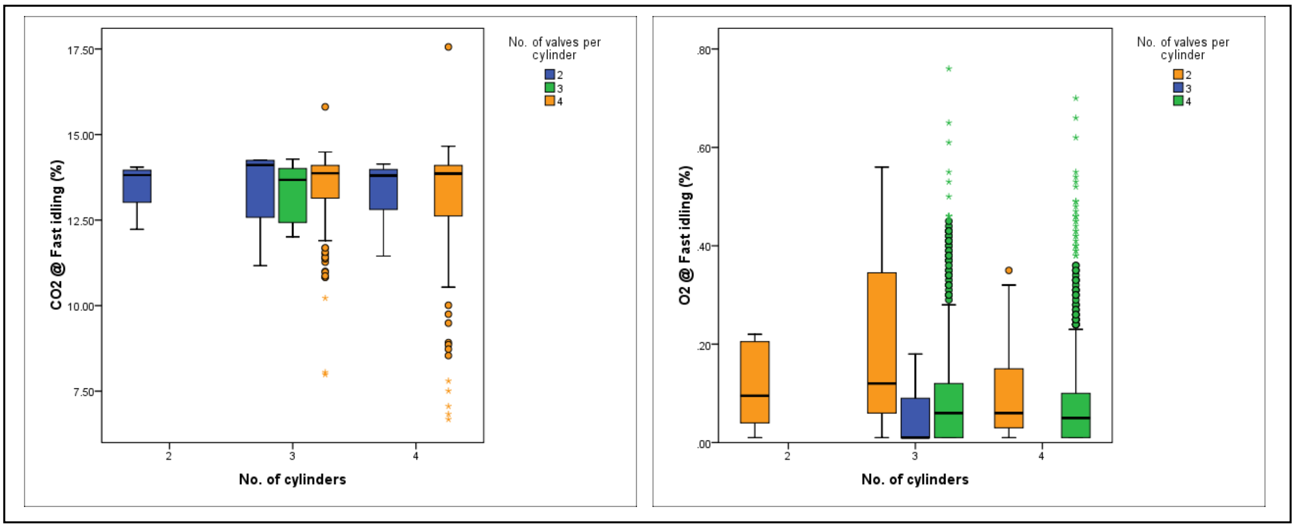


Fig. 4.179 No. of cylinders / valves vs. CO_2 and O_2 emissions (at fast idling)

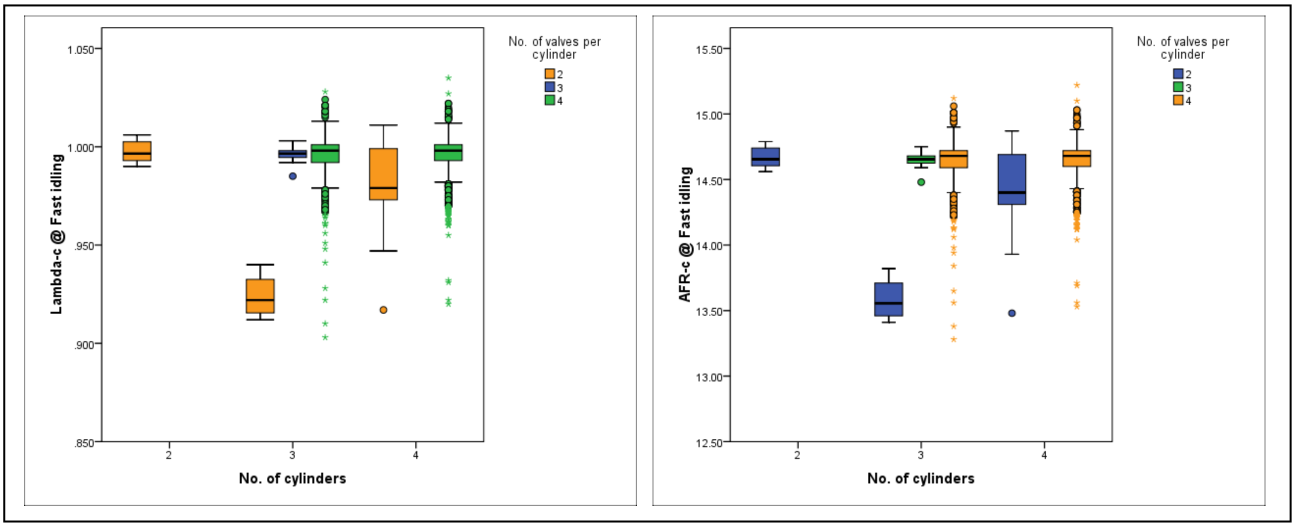


Fig. 4.180 No. of cylinders / valves vs. λ and AFR (at fast idling)

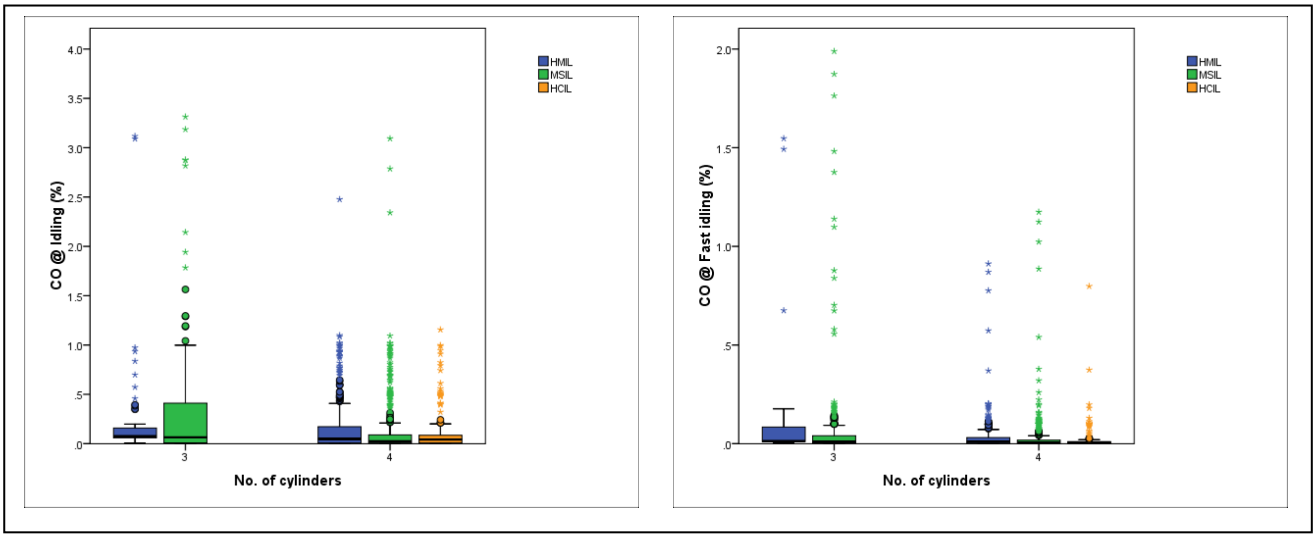


Fig. 4.181 No. of cylinders vs. CO emission - top 3 makes (at idling and fast idling)

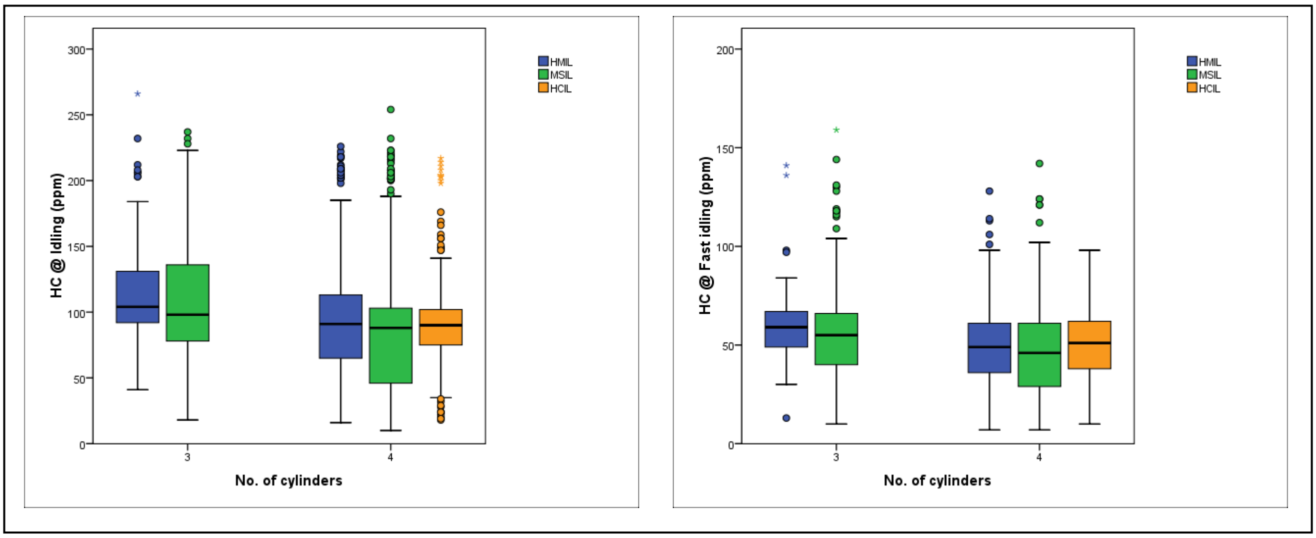


Fig. 4.182 No. of cylinders vs. HC emission - top 3 makes (at idling and fast idling)

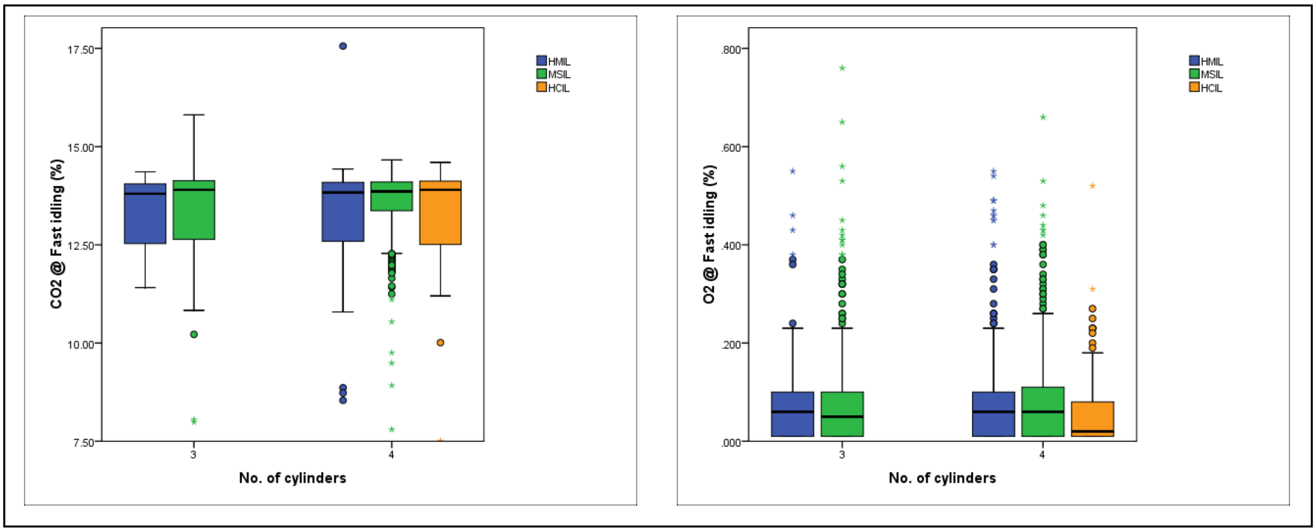


Fig. 4.183 No. of cylinders vs. CO_2 and O_2 emissions - top 3 makes (at fast idling)

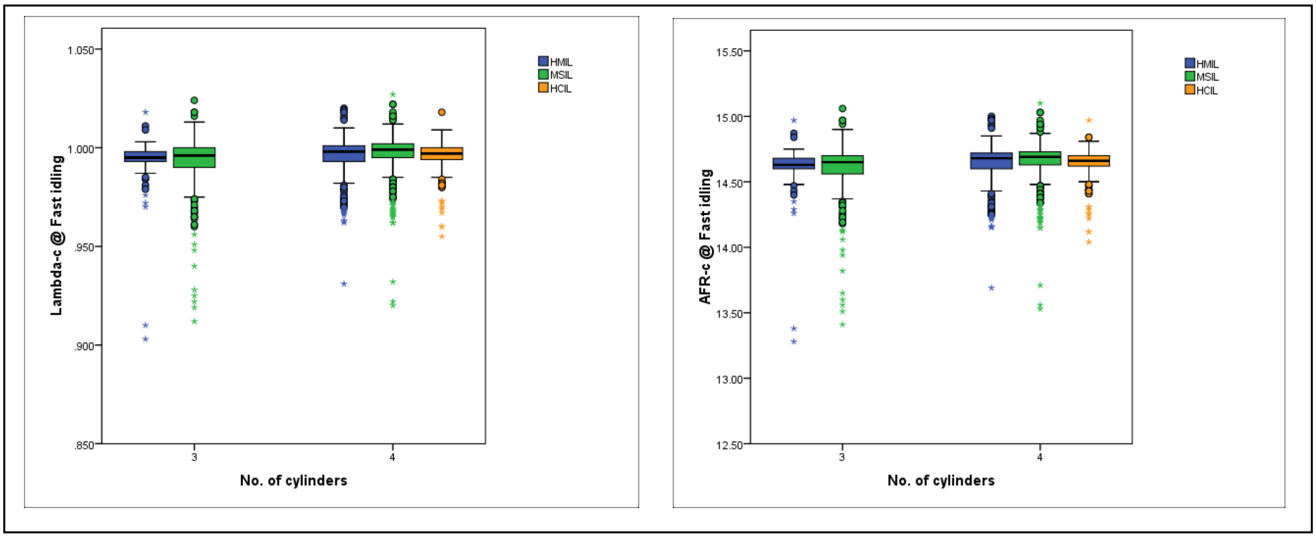


Fig. 4.184 No. of cylinders vs. λ and AFR - top 3 makes (at fast idling)

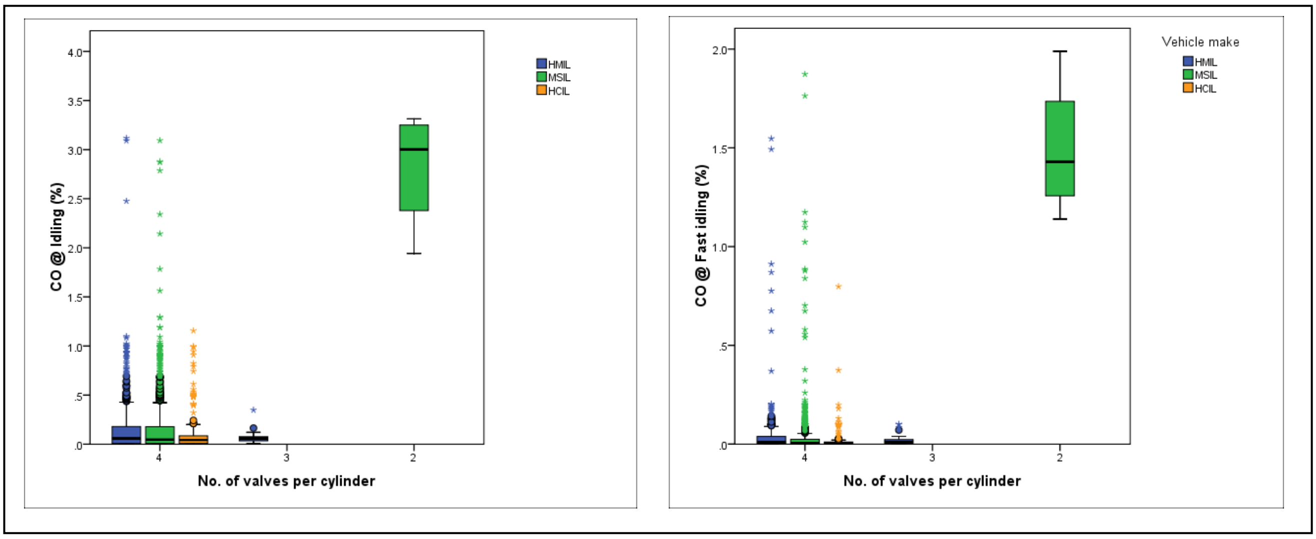


Fig. 4.185 No. of valves / cylinder vs. CO emission - top 3 makes (at idling and fast idling)

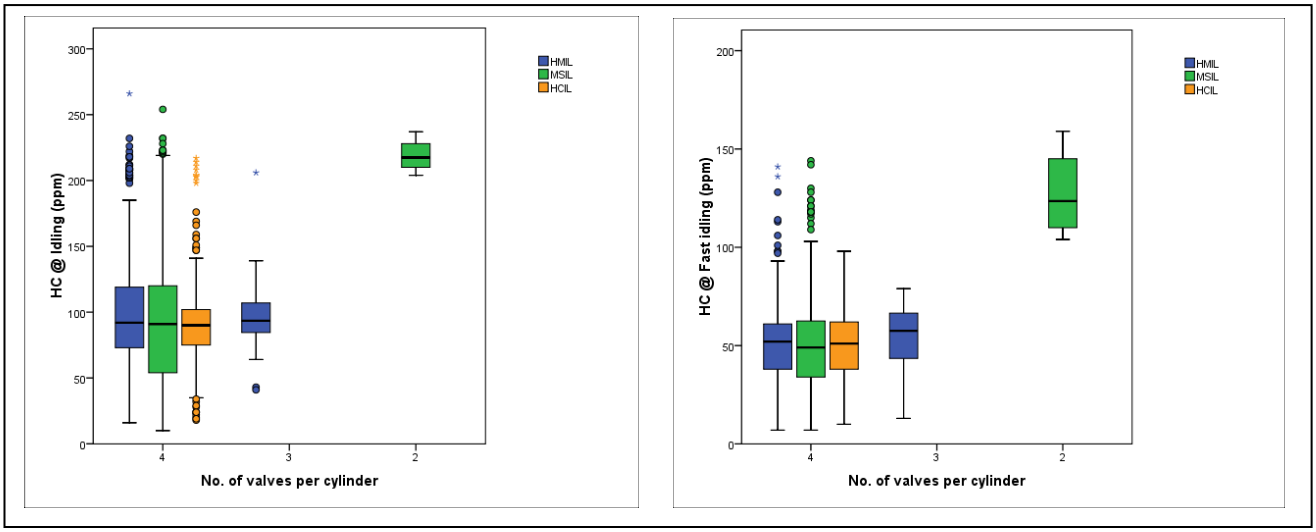


Fig. 4.186 No. of valves / cylinder vs. HC emission - top 3 makes (at idling and fast idling)

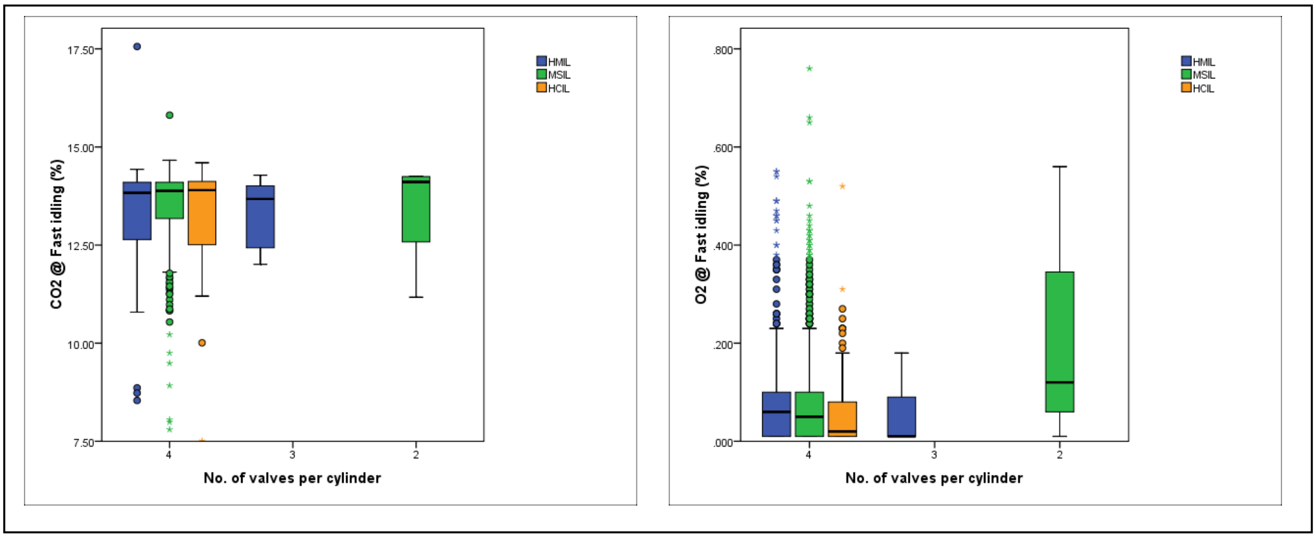


Fig. 4.187 No. of valves / cylinder vs. CO_2 and O_2 emissions - top 3 makes (at fast idling)

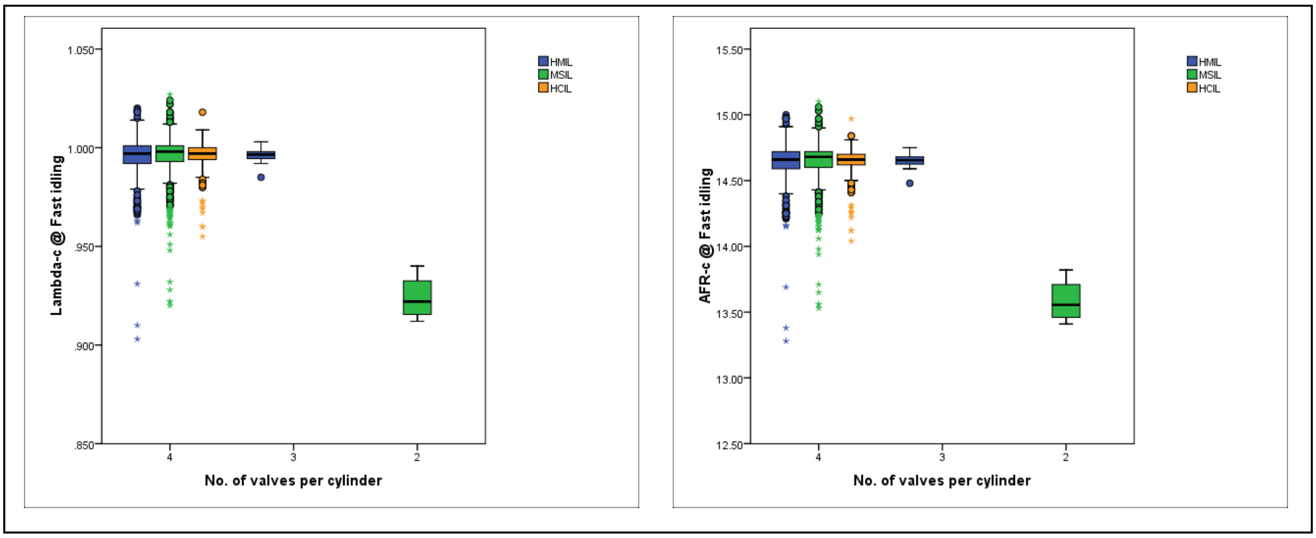


Fig. 4.188 No. of valves / cylinder vs. λ and AFR - top 3 makes (at fast idling)

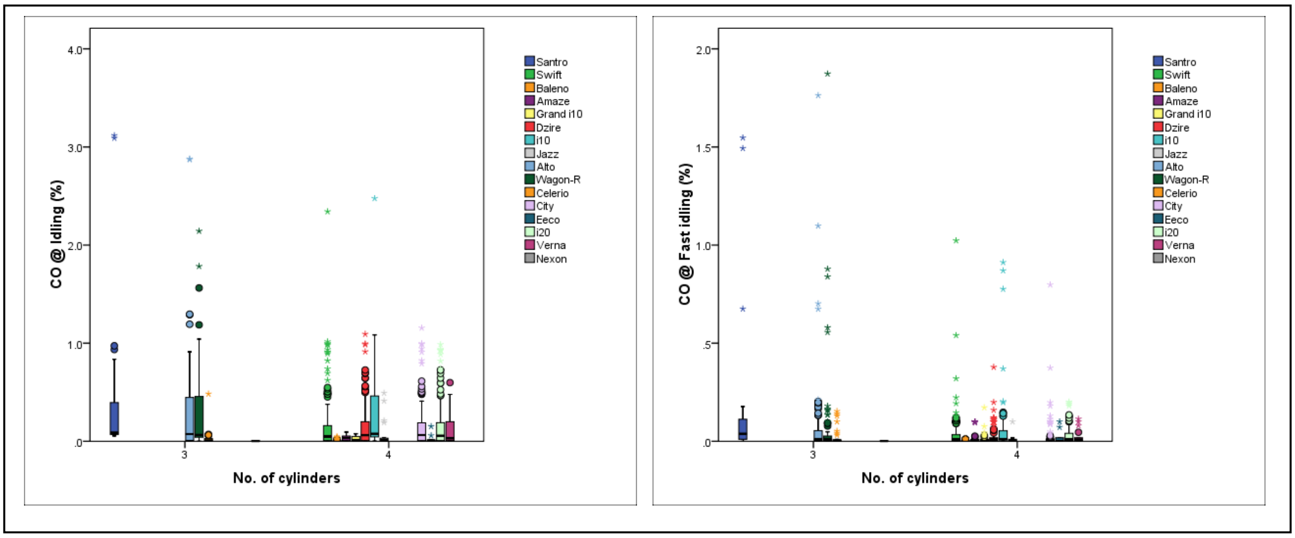


Fig. 4.189 No. of cylinders vs. CO emission - top 16 models (at idling and fast idling)

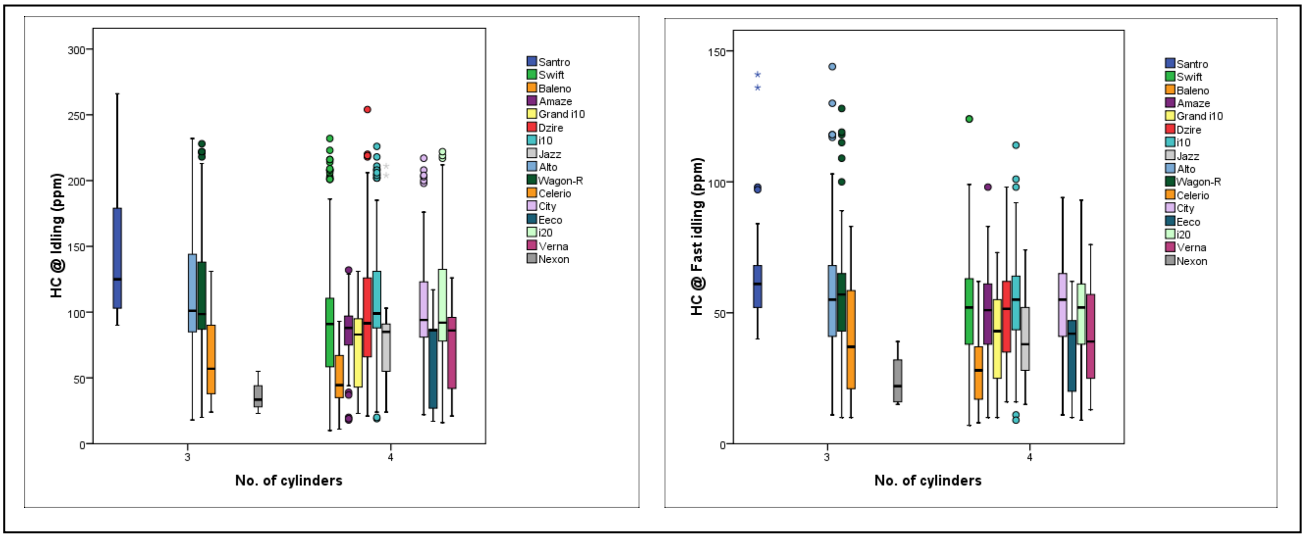


Fig. 4.190 No. of cylinders vs. HC emission - top 16 models (at idling and fast idling)

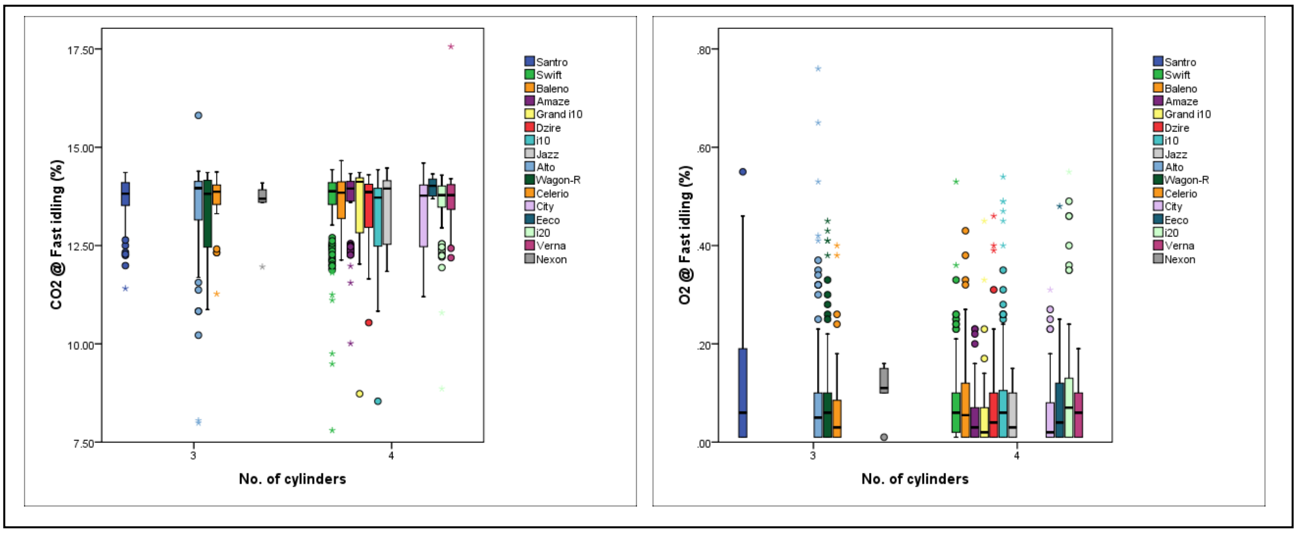


Fig. 4.191 No. of cylinders vs. CO_2 and O_2 emission - top 16 models (at fast idling)

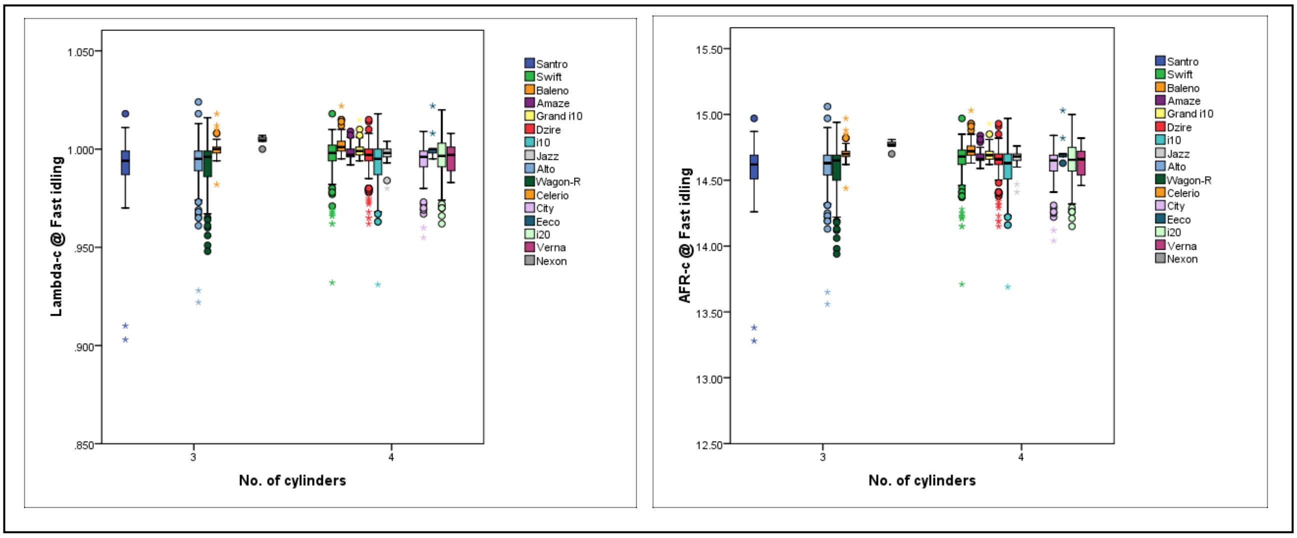


Fig. 4.192 No. of cylinders vs. λ and AFR - top 16 models (at fast idling)

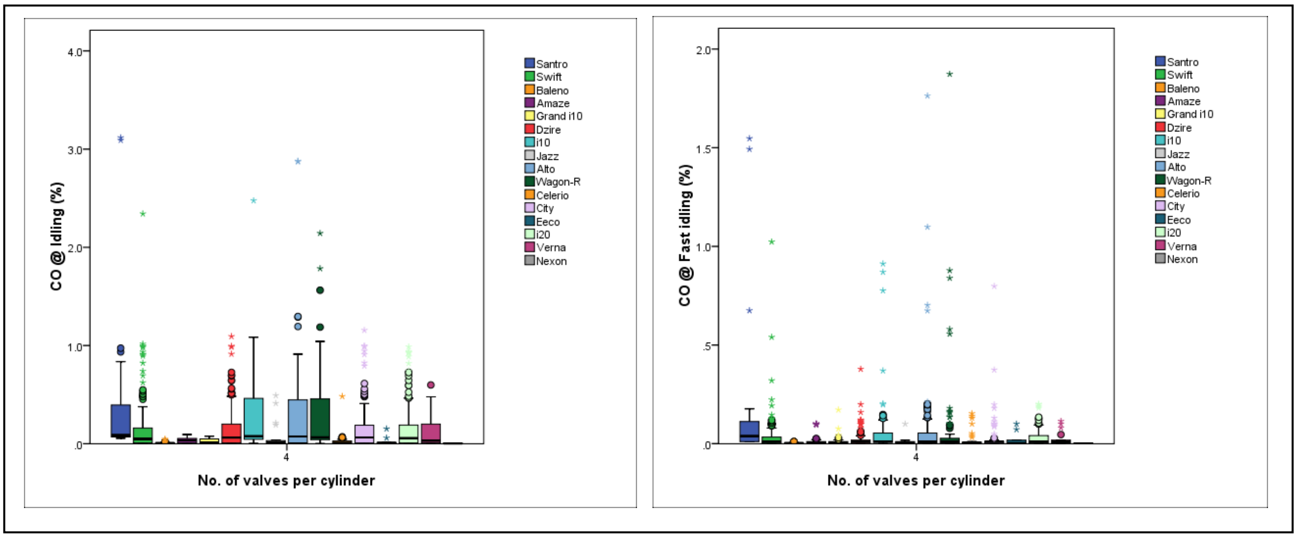


Fig. 4.193 No. of valves / cylinder vs. CO emission - top 16 models (at idling and fast idling)

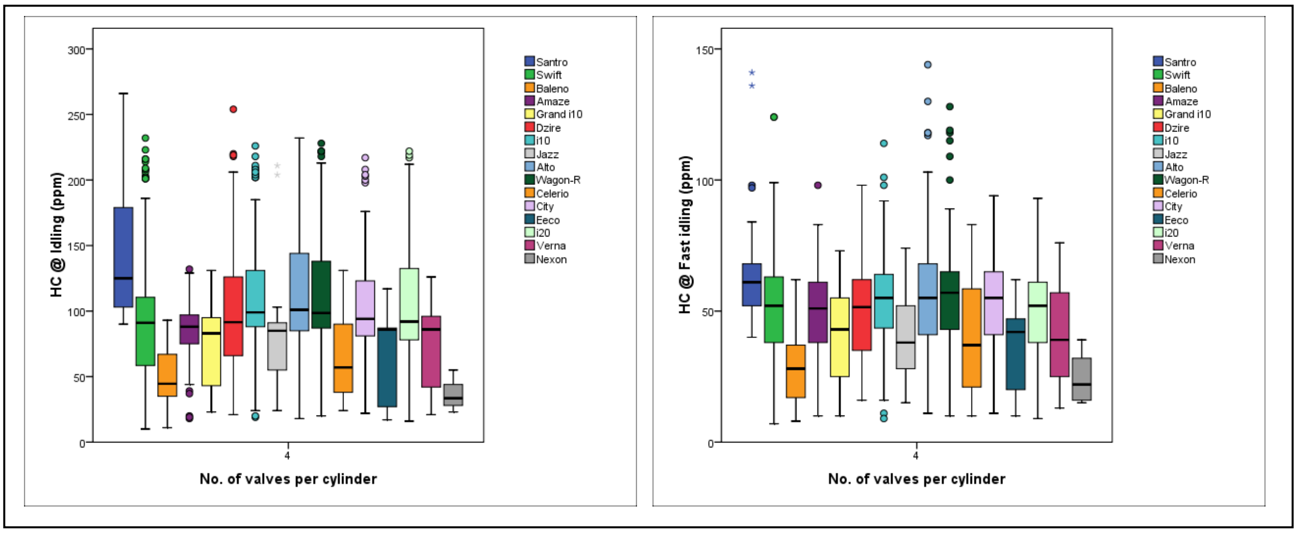


Fig. 4.194 No. of valves / cylinder vs. HC emission - top 16 models (at idling and fast idling)

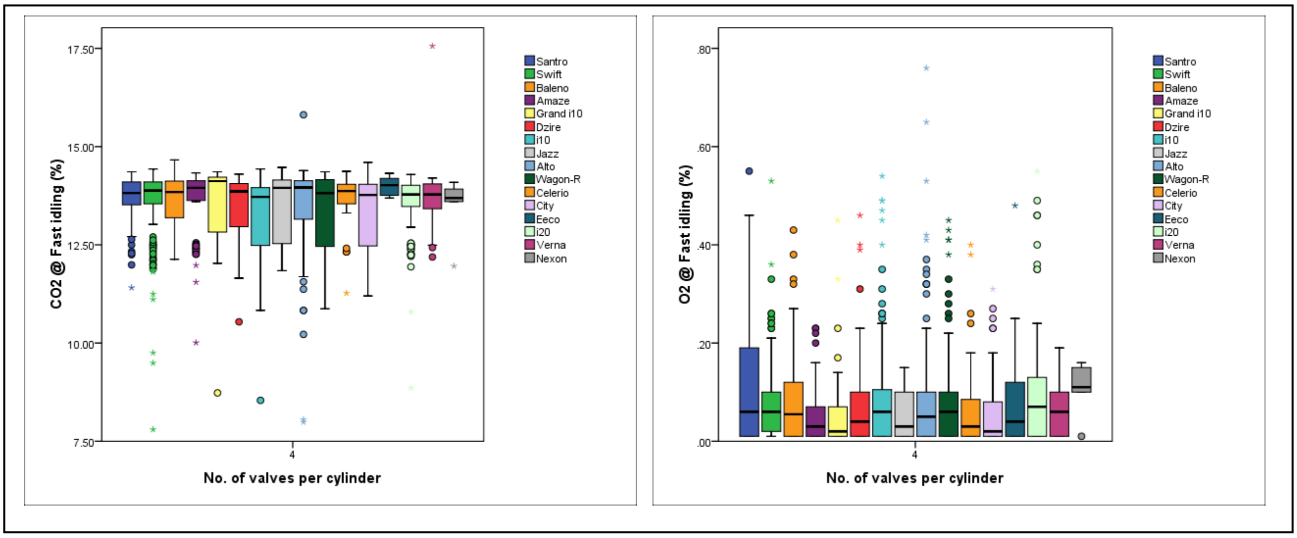


Fig. 4.195 No. of valves / cylinder vs. CO_2 and O_2 emission - top 16 models (at fast idling)

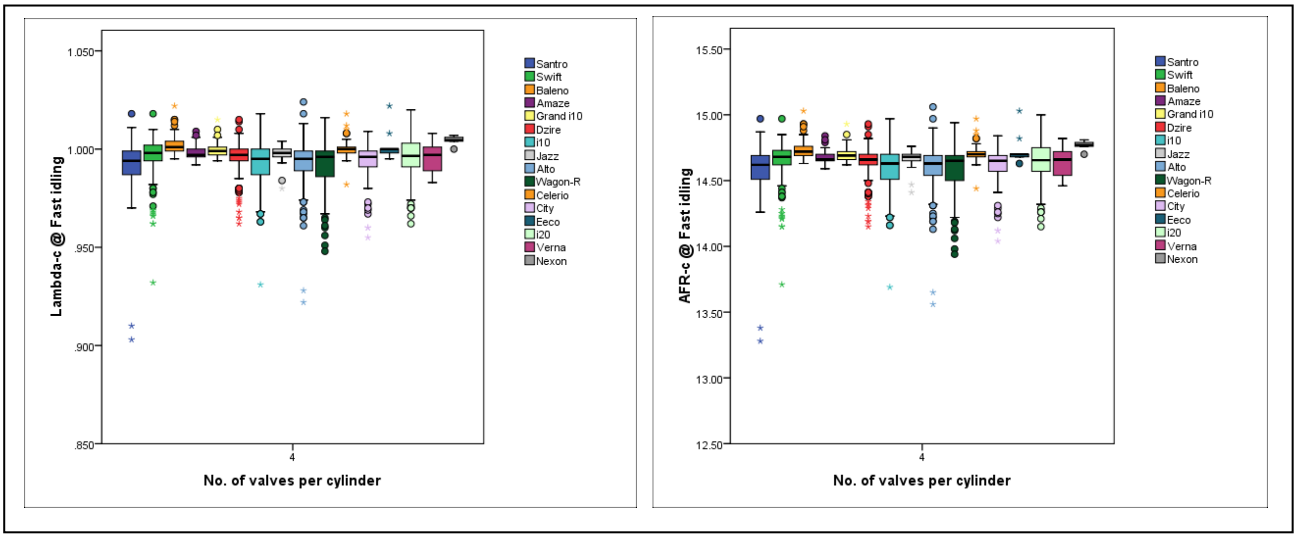


Fig. 4.196 No. of valves / cylinder vs. λ and AFR - top 16 models (at fast idling)

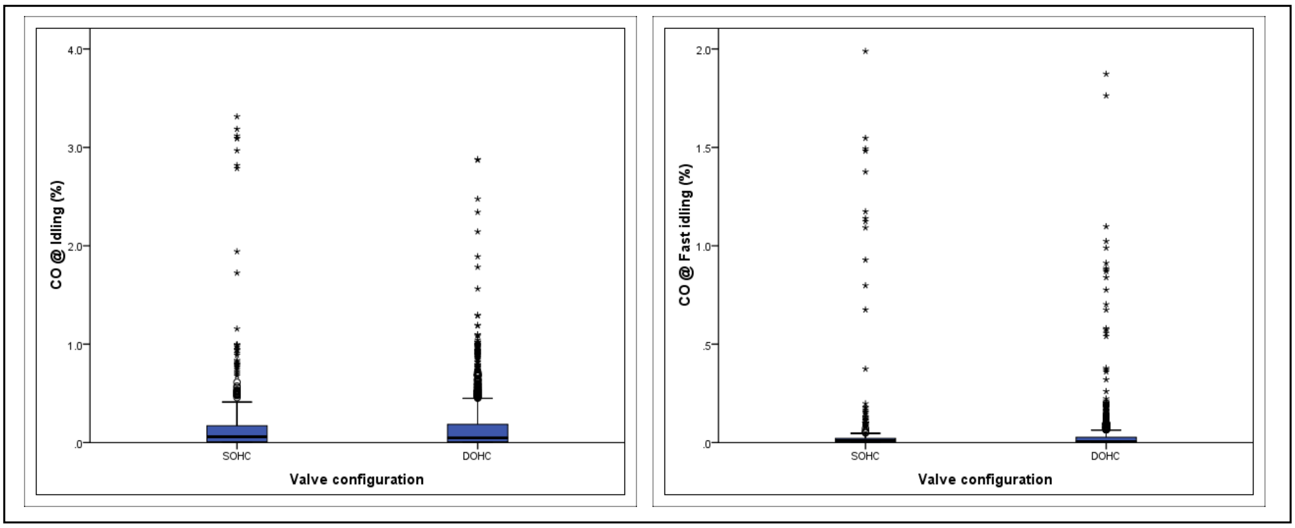


Fig. 4.197 Valve configuration vs. CO emission (at idling and fast idling)

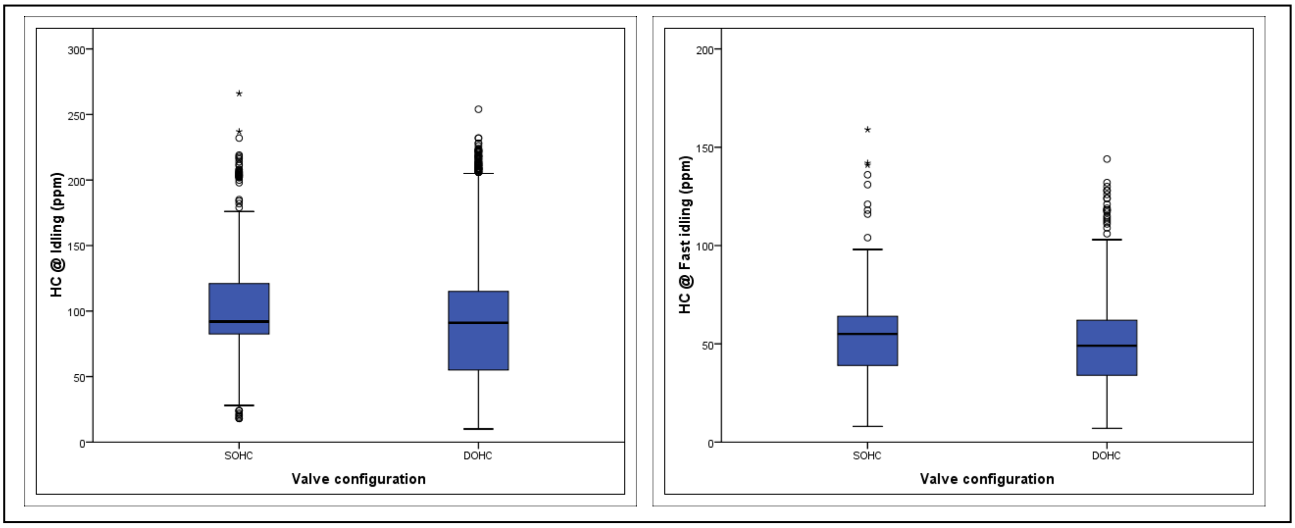


Fig. 4.198 Valve configuration vs. HC emission (at idling and fast idling)

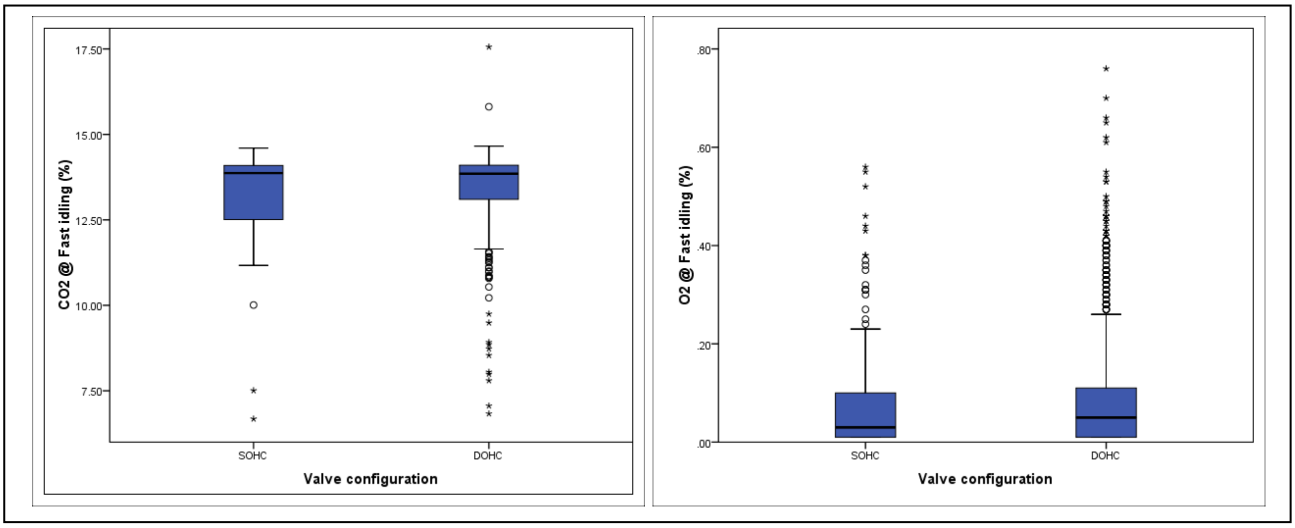


Fig. 4.199 Valve configuration vs. CO_2 and O_2 emissions (at fast idling)

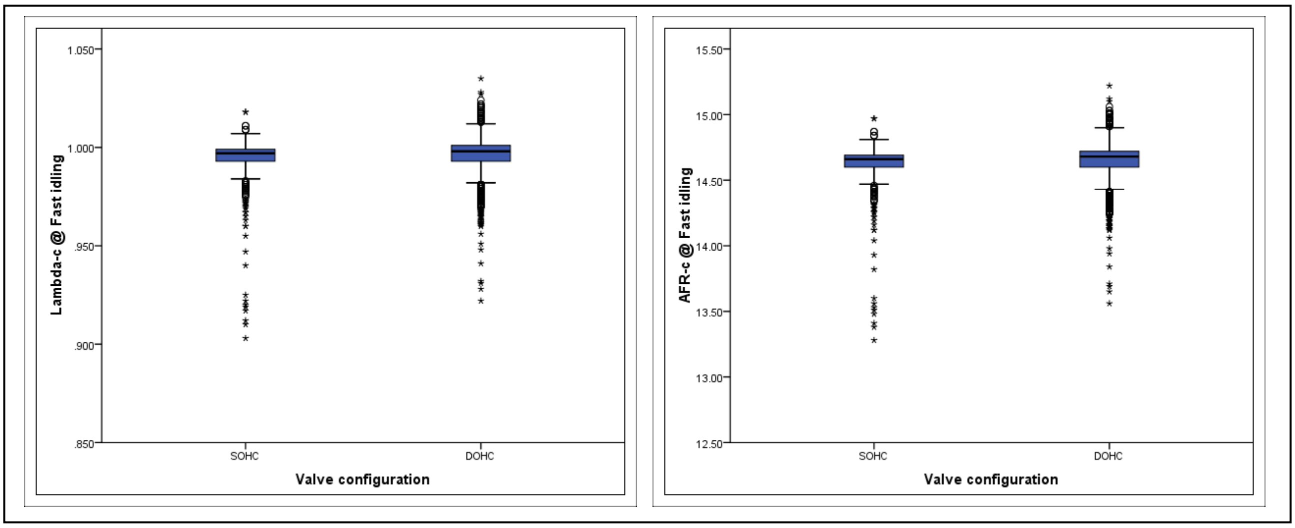


Fig. 4.200 Valve configuration vs. λ and AFR (at fast idling)

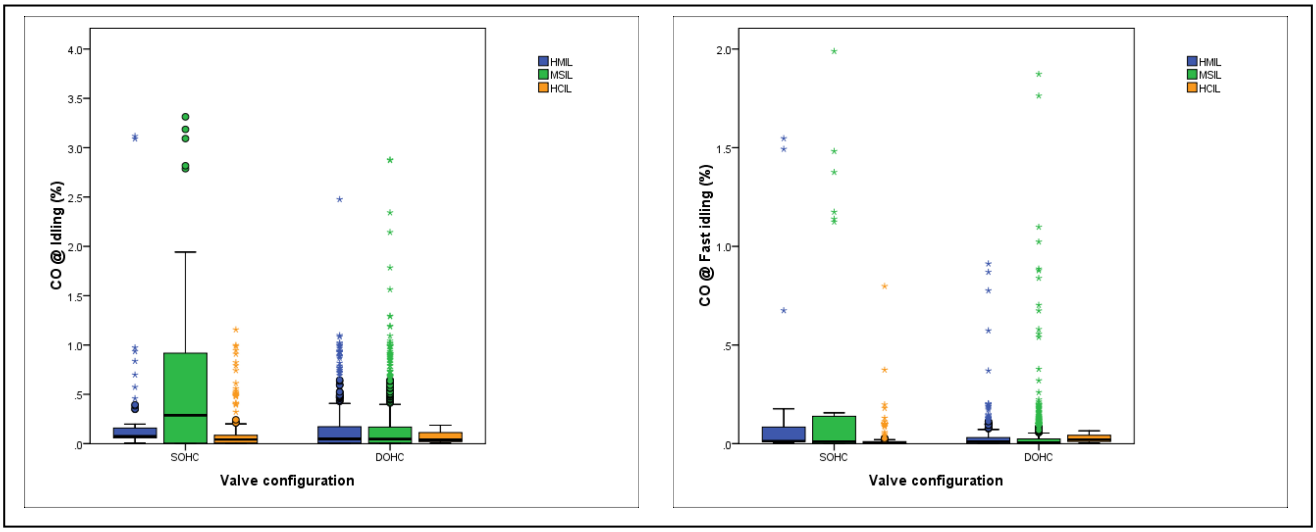


Fig. 4.201 Valve configuration vs. CO emission - top 3 makes (at idling and fast idling)

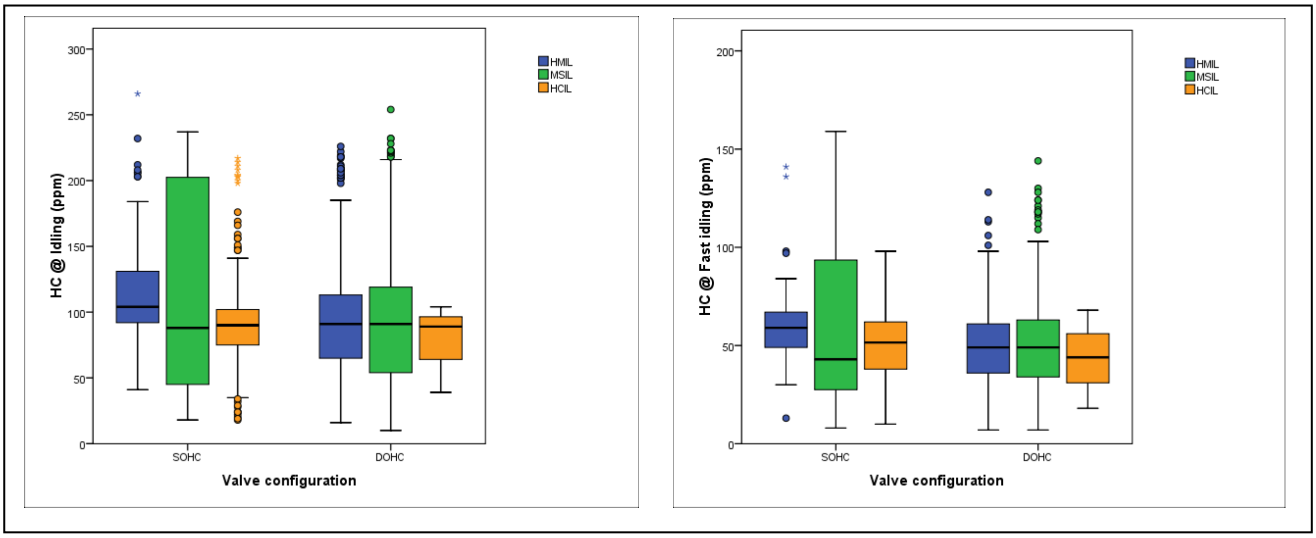


Fig. 4.202 Valve configuration vs. HC emission - top 3 makes (at idling and fast idling)

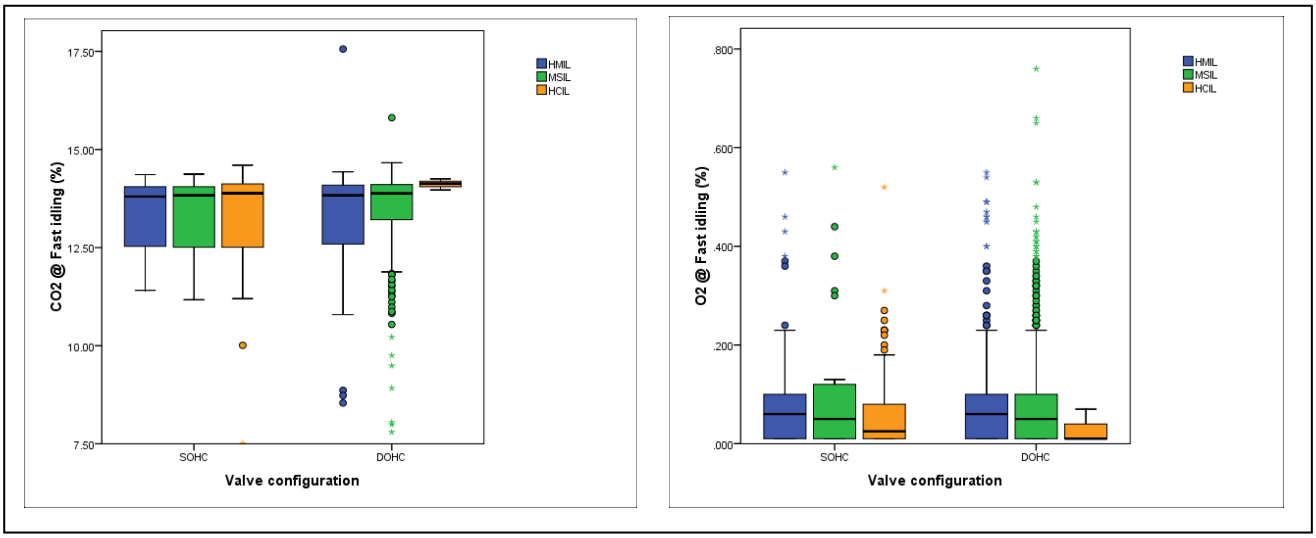


Fig. 4.203 Valve configuration vs. CO_2 and O_2 emissions - top 3 makes (at fast idling)

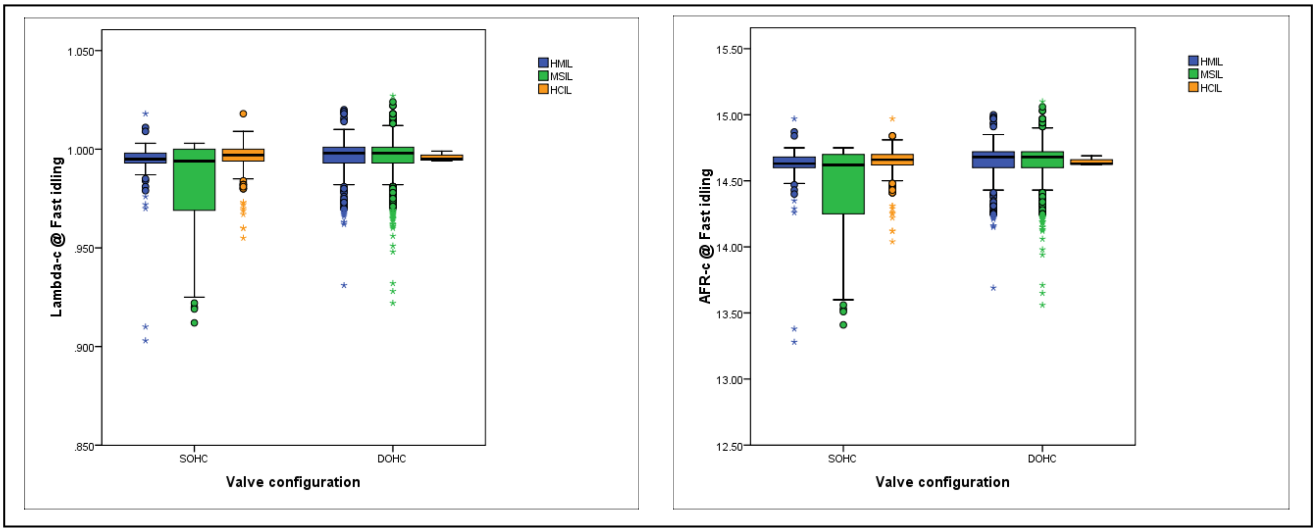


Fig. 4.204 Valve configuration vs. λ and AFR - top 3 makes (at fast idling)

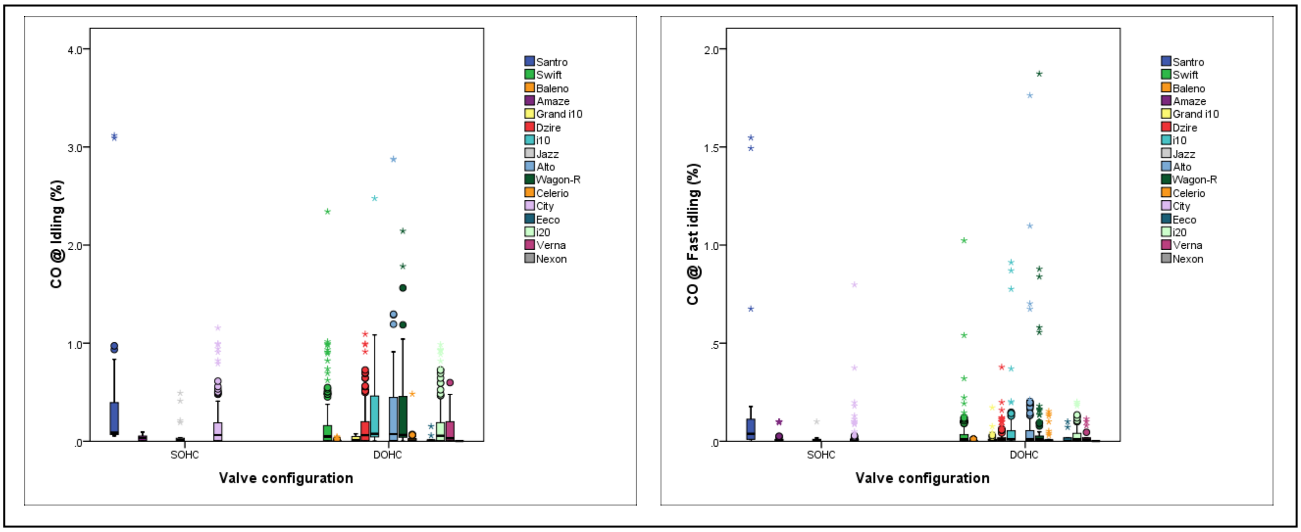


Fig. 4.205 Valve configuration vs. CO emission - top 16 models (at idling and fast idling)

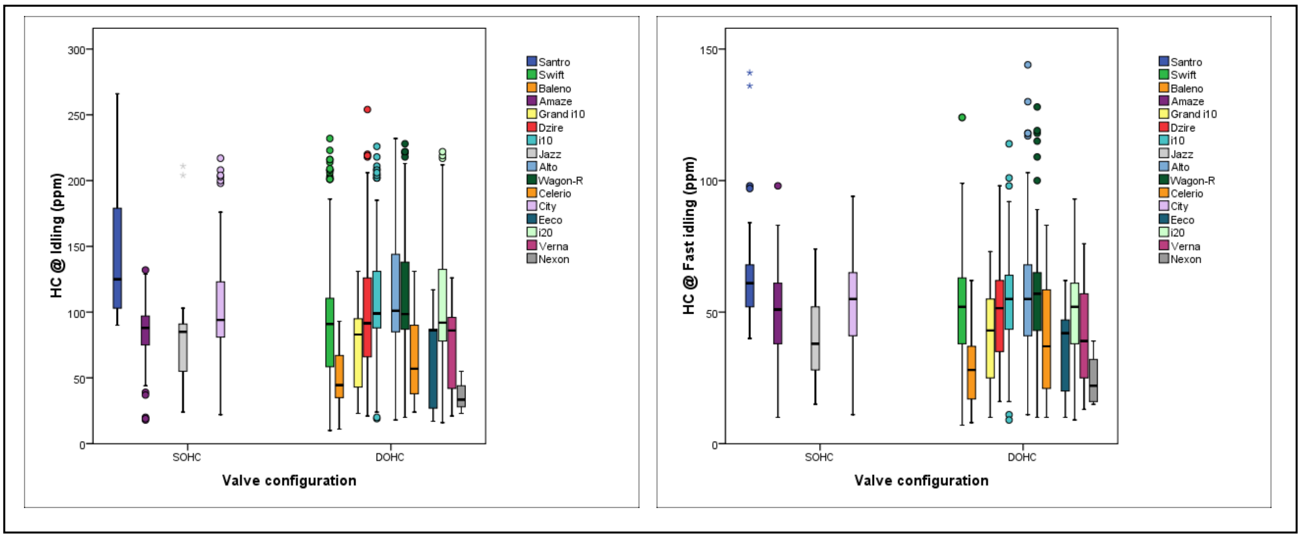


Fig. 4.206 Valve configuration vs. HC emission - top 16 models (at idling and fast idling)

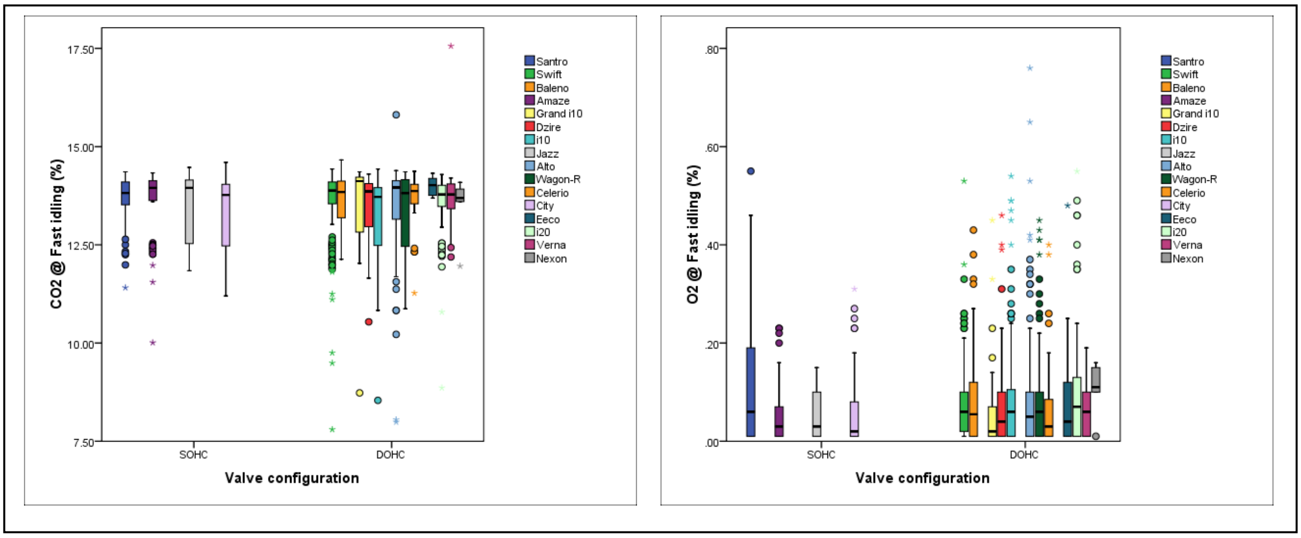


Fig. 4.207 Valve configuration vs. CO_2 and O_2 emission - top 16 models (at fast idling)

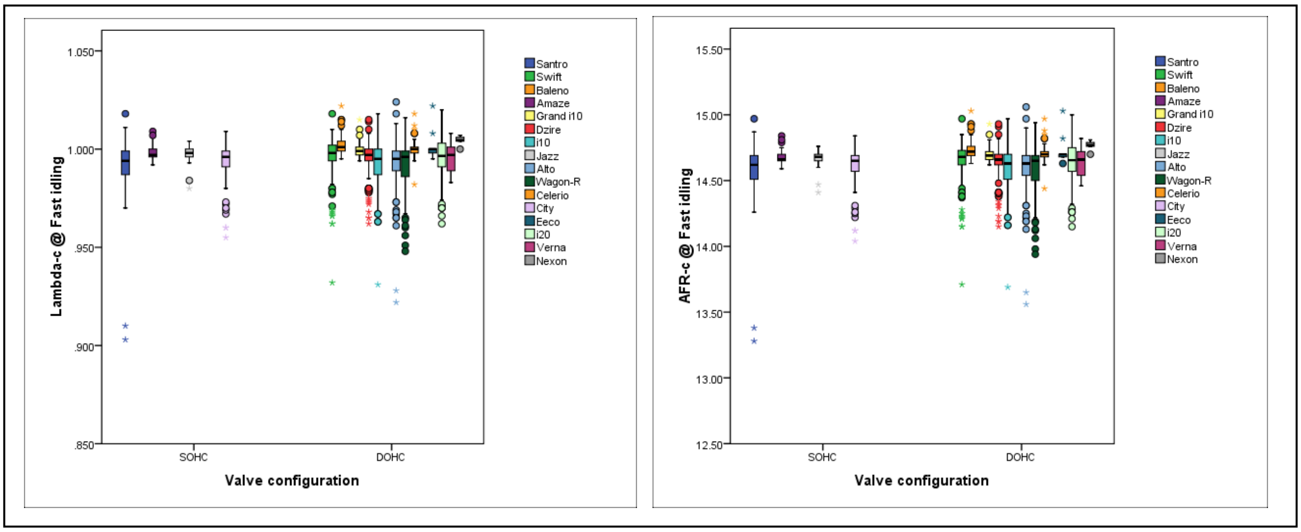


Fig. 4.208 Valve configuration vs. λ and AFR - top 16 models (at fast idling)

On the other hand, two (2) engine-related independent variables, i.e., engine aspiration type, and fuel mixing conditions were found to be related with the tailpipe parameters for all three dataset conditions. Turbo-charged engines were found to emit lower ranges of both CO and HC under both idle and fast idle testing modes compared to naturally aspirated ones (Figs. 4.209 – 4.210). As the turbocharger induces entry of more ambient air into the combustion chamber of the engine, and therefore more burning of fuel per unit time, the CO and HC had more chances of converting into CO_2 reducing their concentration in the tailpipe exhaust. Also, the amount of O_2 would have increased in the tailpipe exhaust. While the boxplots depict an apparent increase in O_2 concentration in the whole dataset scenario, a proportionate increase in CO_2 could not be seen (Fig. 4.211). A reason could be a very less number of vehicles in the sample (only 0.63 % petrol-driven cars had turbo-charging). λ and AFR remained unchanged for engine aspiration type (Fig. 4.212). Analysis of the top 3 makes and 16 models shows that the top 3 makes did not have any turbo-charged car; the top 16 models had only one case of the turbo-charged engine (Verna) which depicted result similar to the entire dataset (Figs. 4.213 – 4.220).

The fuel mixing conditions also reported a good relationship with the tailpipe emission. CO and HC had the lowest ranges of emission of CO and HC in idling and fast idling test modes during stoichiometric fuel mixing or burning condition, relatively higher during lean and the highest during rich fuel burning scenario prevalent in the engine’s combustion chamber (Fig. 4.221 – 4.222). The make and model-wise scenarios were also similar (Figs. 4.225 – 4.232).

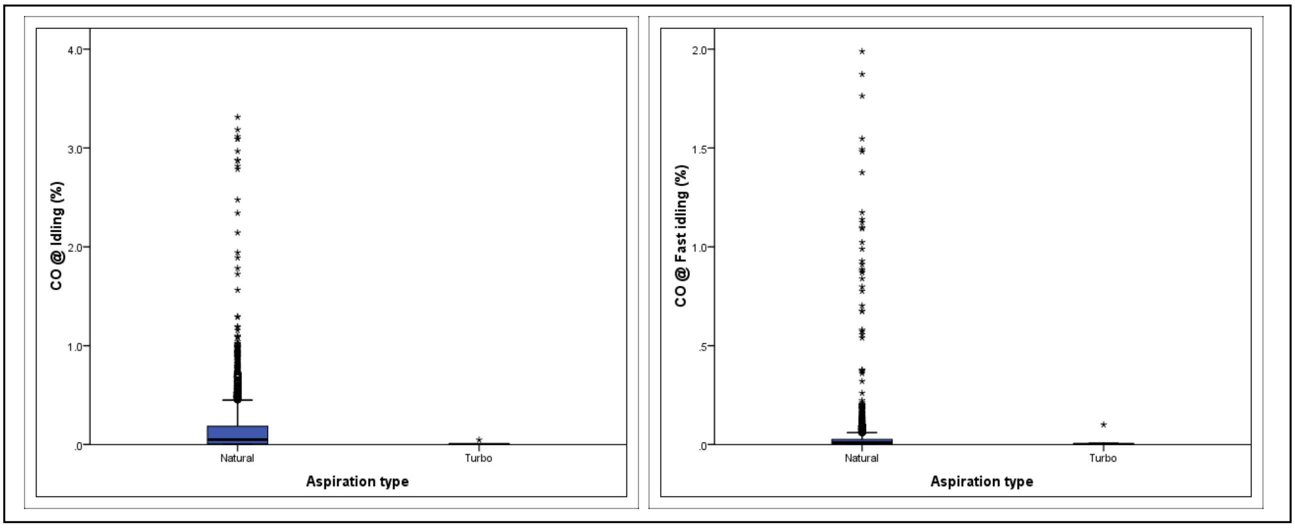


Fig. 4.209 Engine aspiration vs. CO emission (at idling and fast idling)

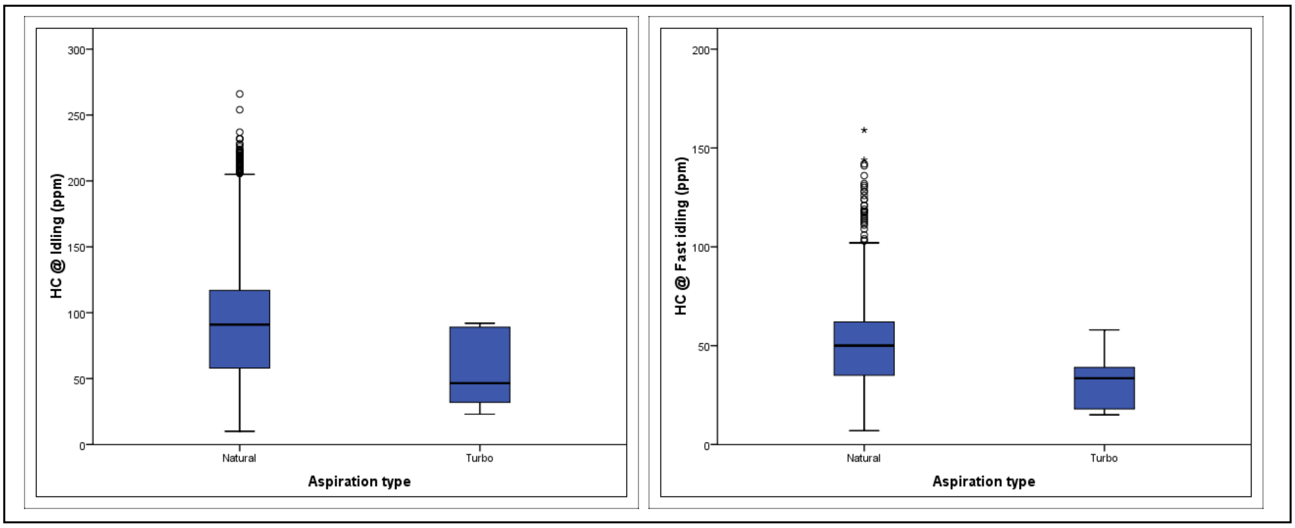


Fig. 4.210 Engine aspiration vs. HC emission (at idling and fast idling)

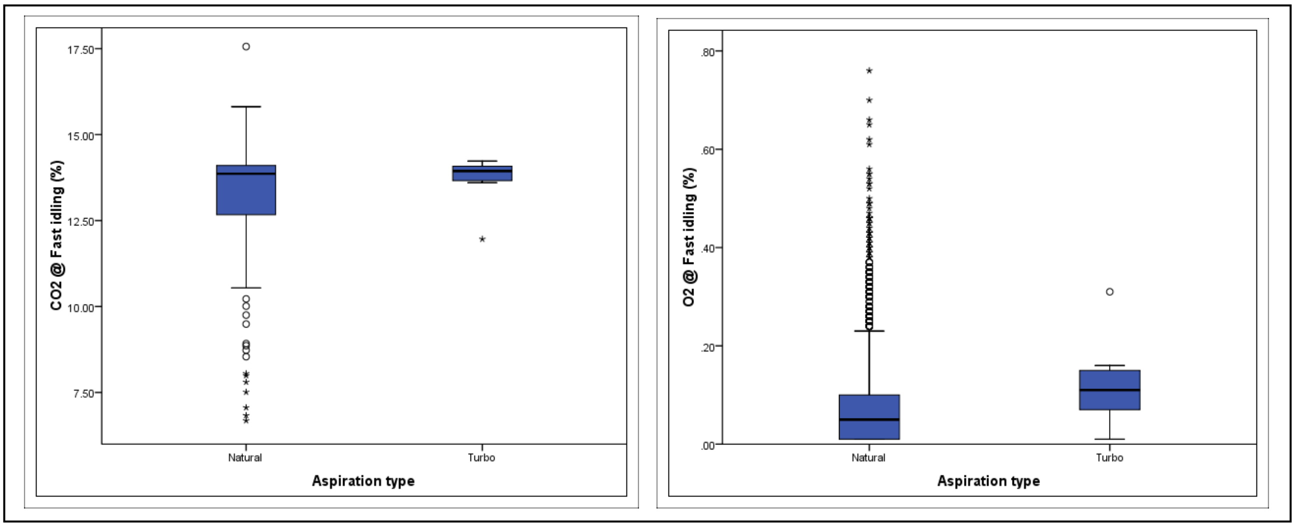


Fig. 4.211 Engine aspiration vs. CO_2 and O_2 emissions (at fast idling)

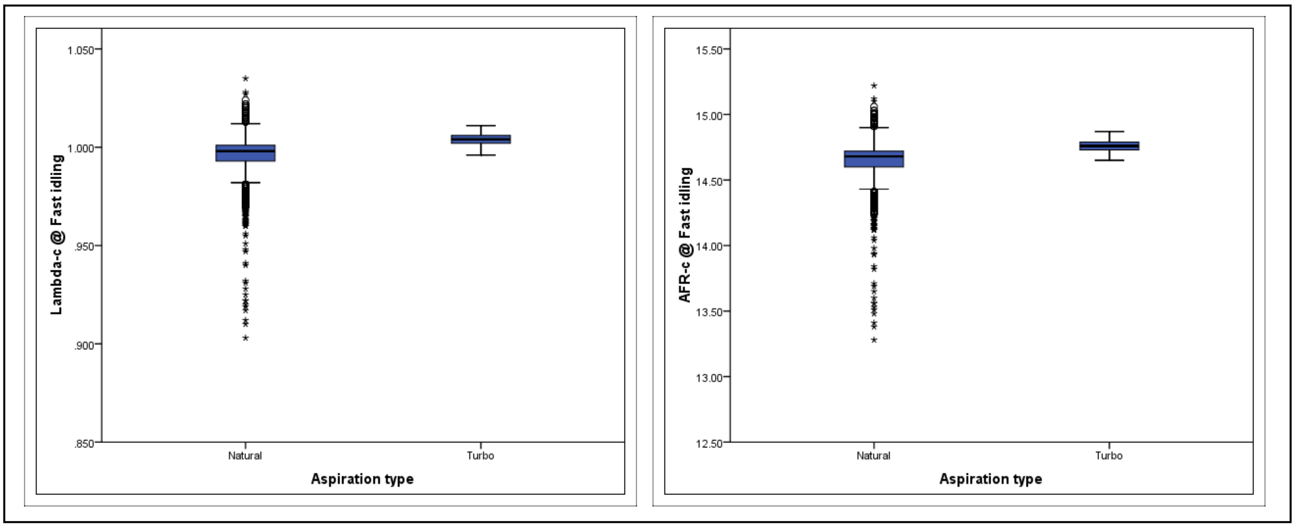


Fig. 4.212 Engine aspiration vs. λ and AFR (at fast idling)

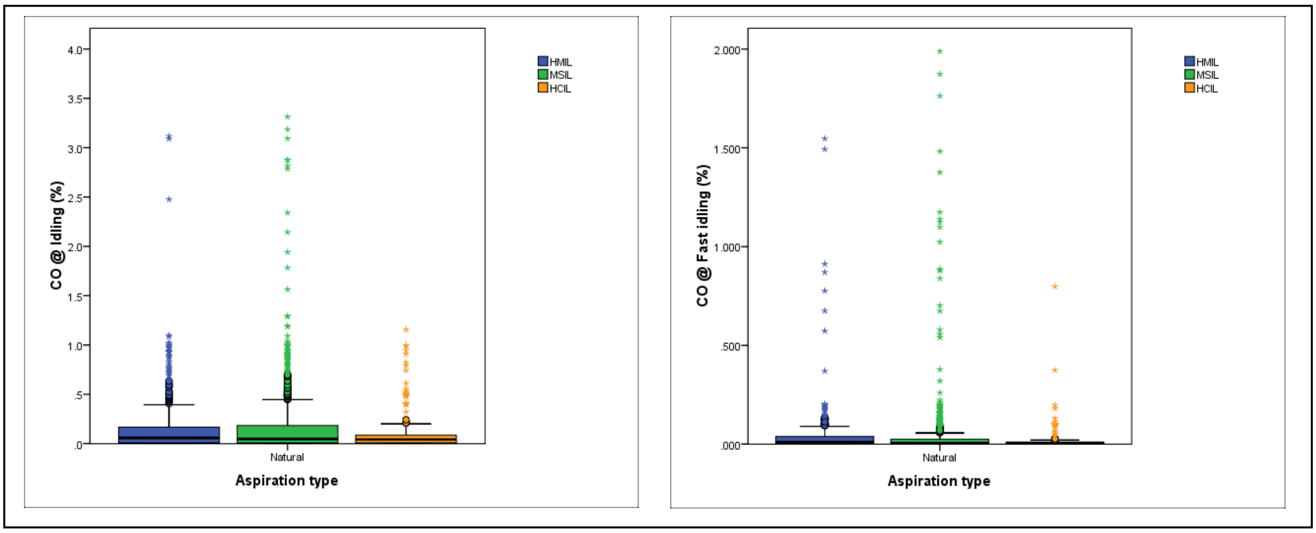


Fig. 4.213 Engine aspiration vs. CO emission - top 3 makes (at idling and fast idling)

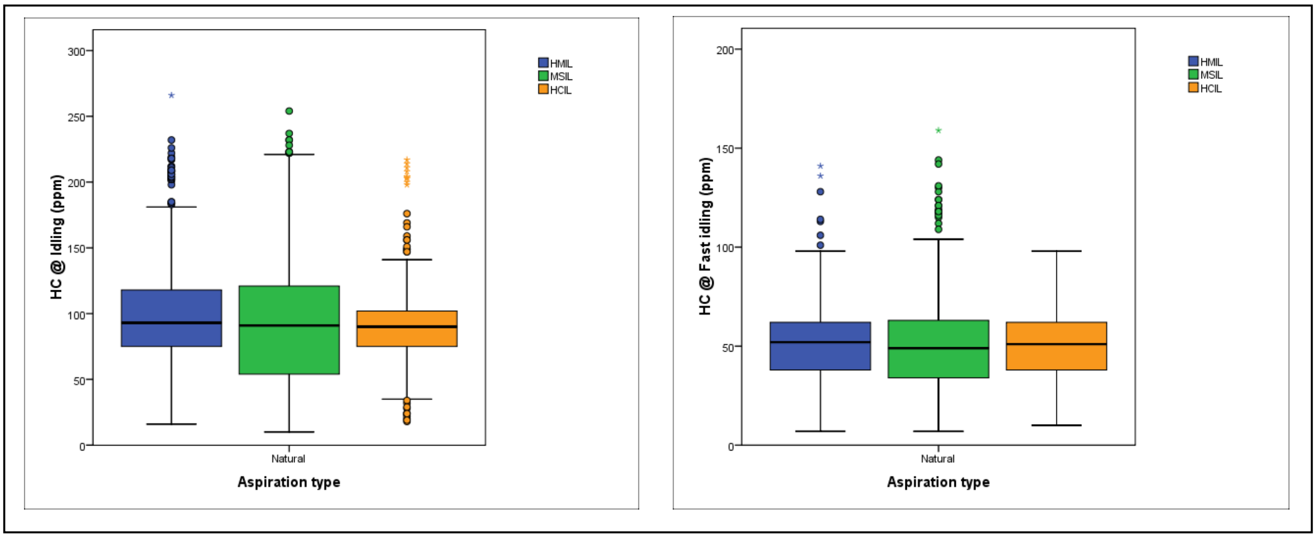


Fig. 4.214 Engine aspiration vs. HC emission - top 3 makes (at idling and fast idling)

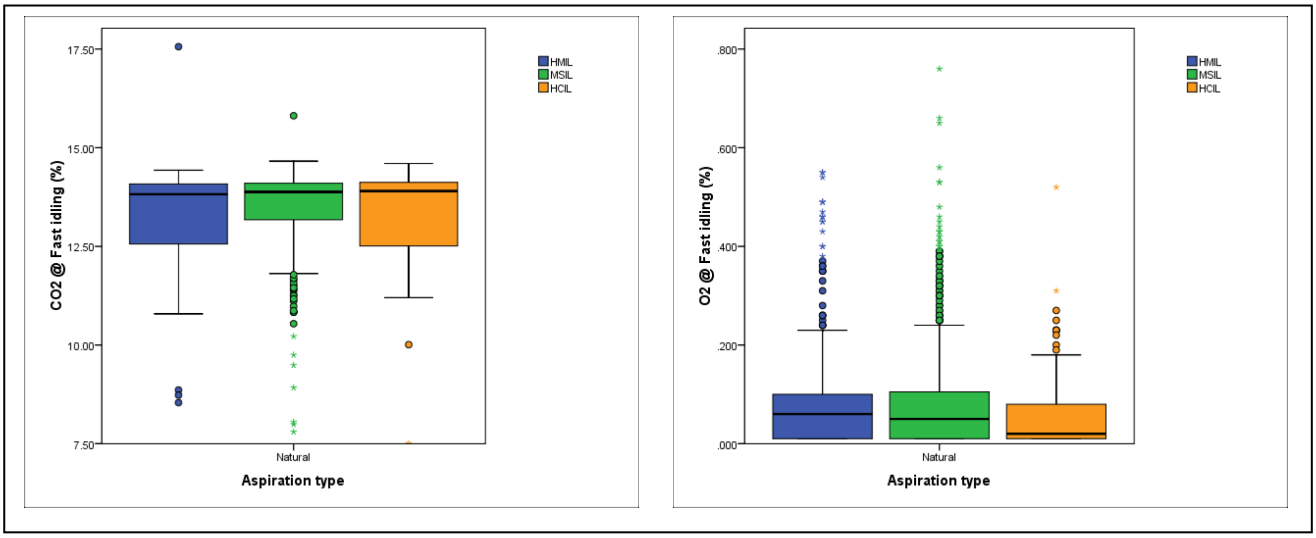


Fig. 4.215 Engine aspiration vs. CO_2 and O_2 emissions - top 3 makes (at fast idling)

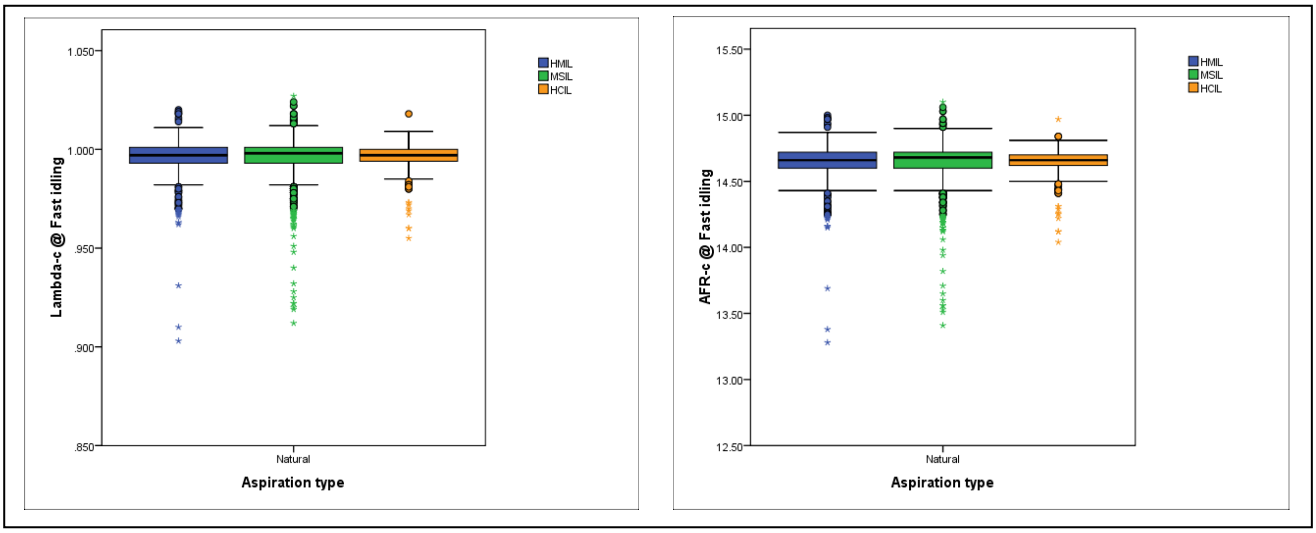


Fig. 4.216 Engine aspiration vs. λ and AFR - top 3 makes (at fast idling)

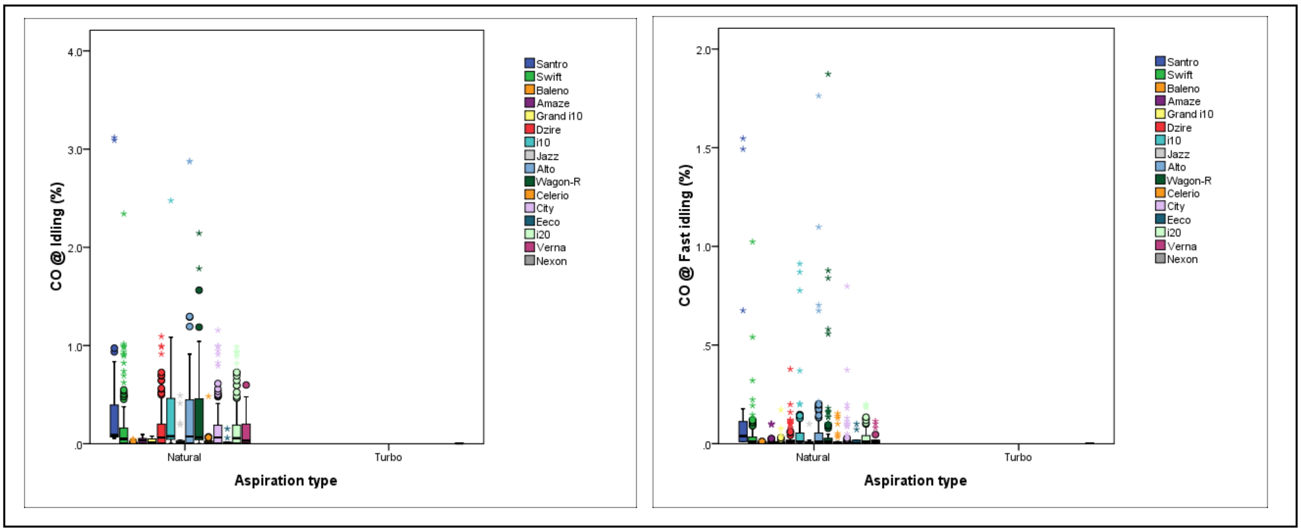


Fig. 4.217 Engine aspiration vs. CO emission - top 16 models (at idling and fast idling)

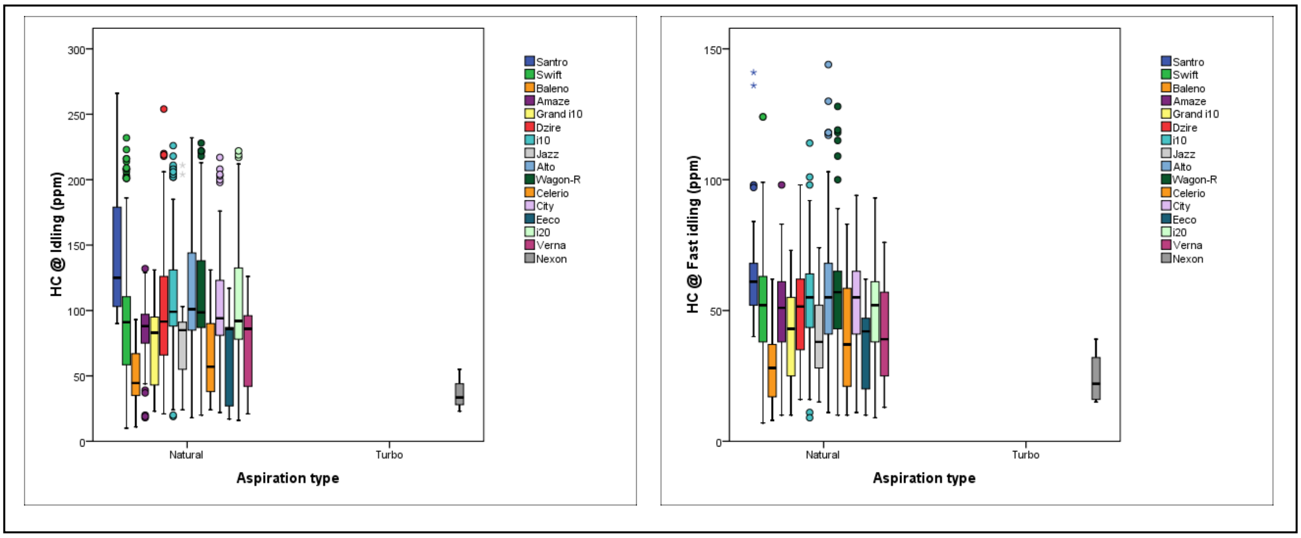


Fig. 4.218 Engine aspiration vs. HC emission - top 16 models (at idling and fast idling)

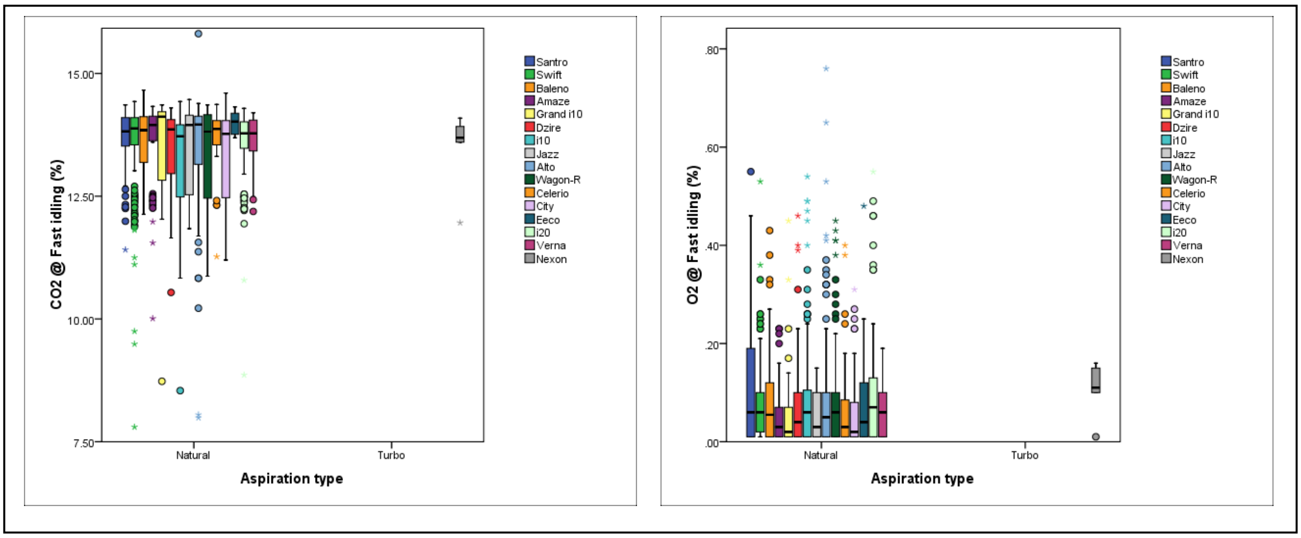


Fig. 4.219 Engine aspiration vs. CO_2 and O_2 emission - top 16 models (at fast idling)

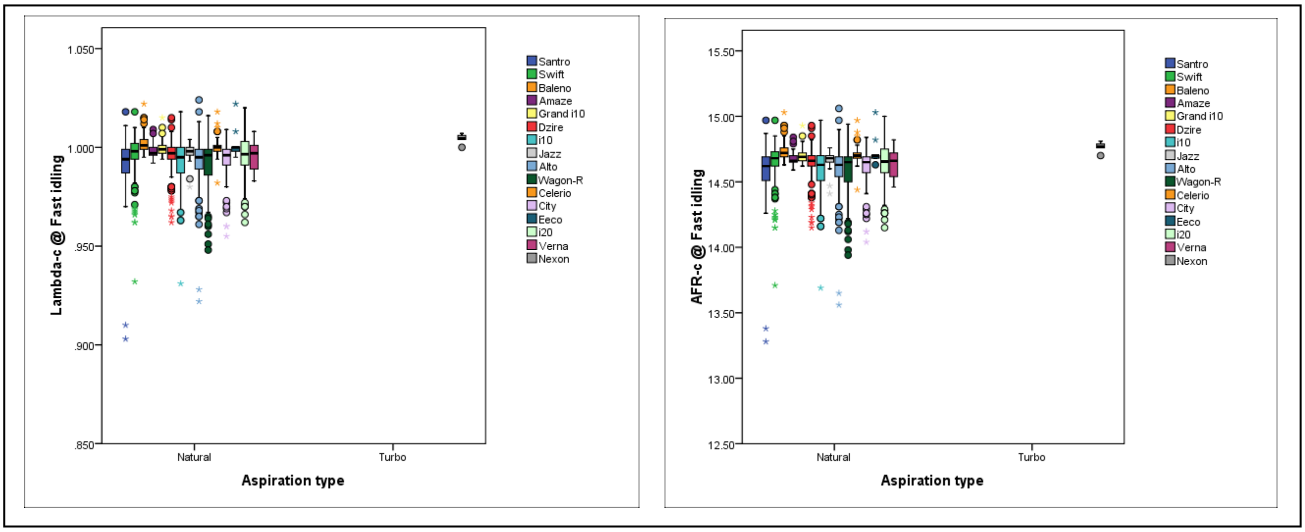


Fig. 4.220 Engine aspiration vs. λ and AFR - top 16 models (at fast idling)

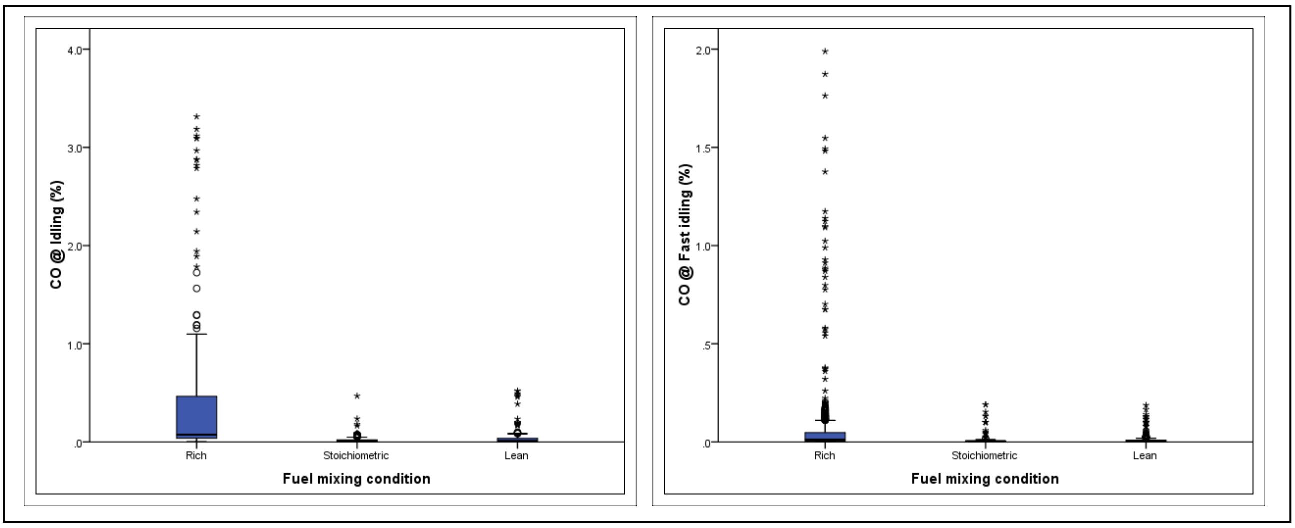


Fig. 4.221 Fuel mixing condition vs. CO emission (at idling and fast idling)

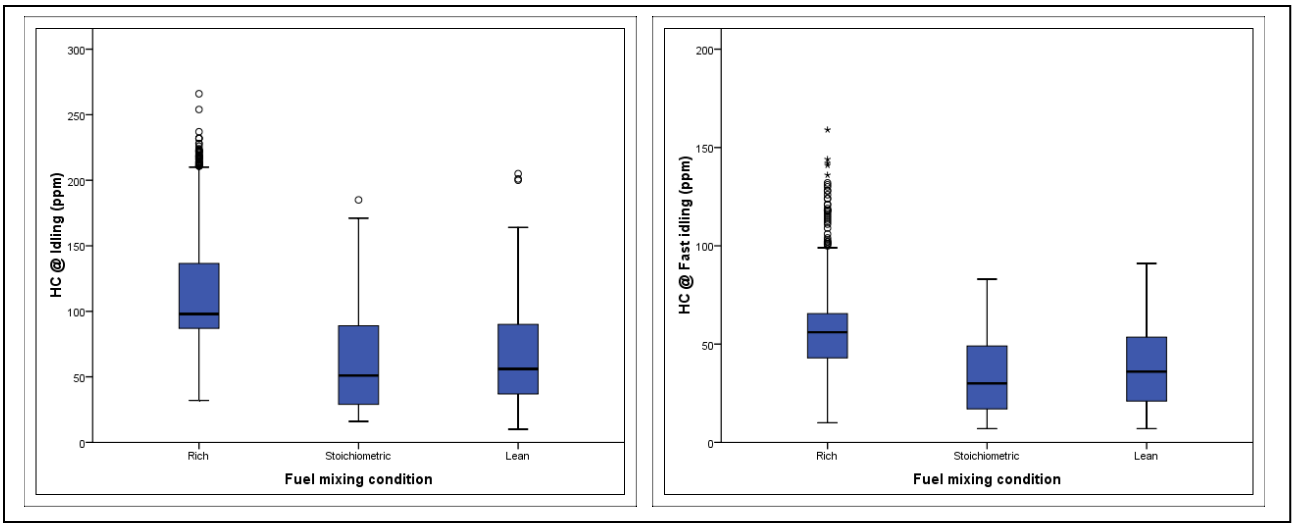


Fig. 4.222 Fuel mixing condition vs. HC emission (at idling and fast idling)

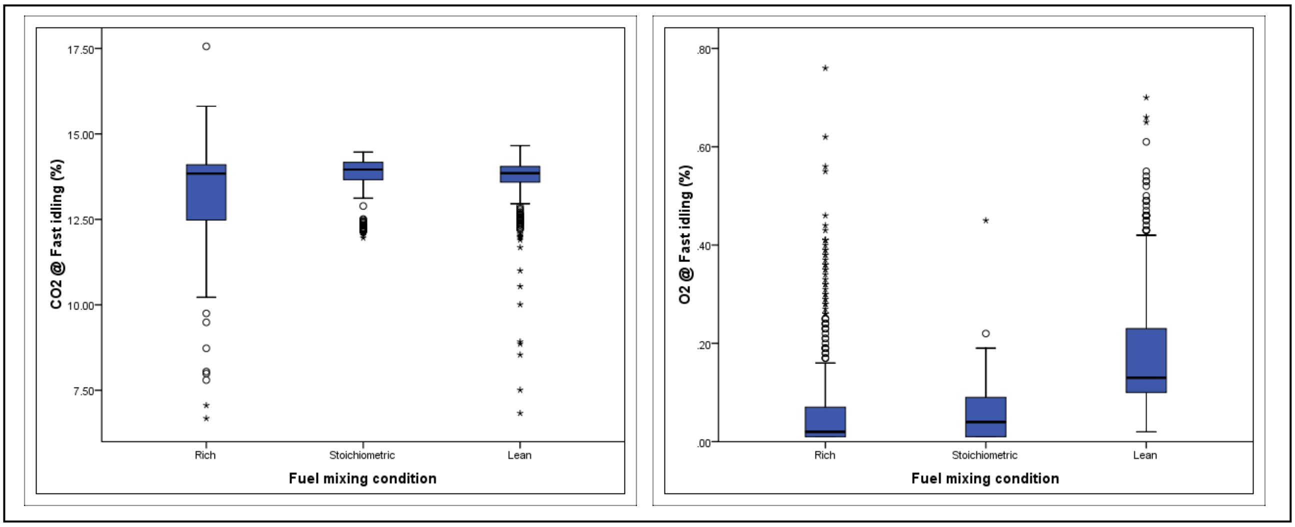


Fig. 4.223 Fuel mixing condition vs. CO_2 and O_2 emissions (at fast idling)

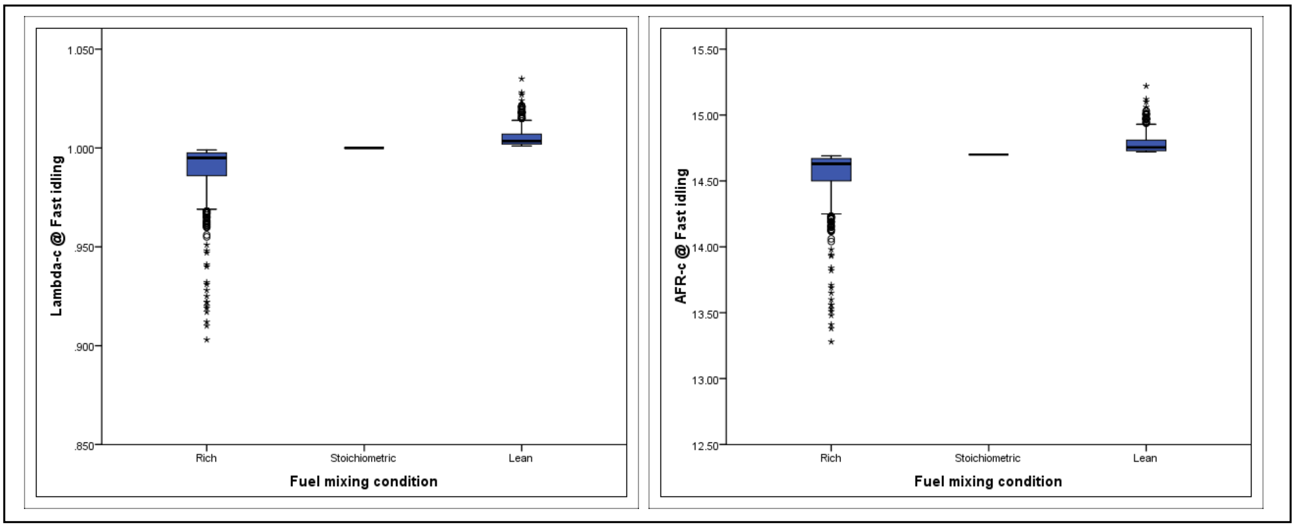


Fig. 4.224 Fuel mixing condition vs. λ and AFR (at fast idling)

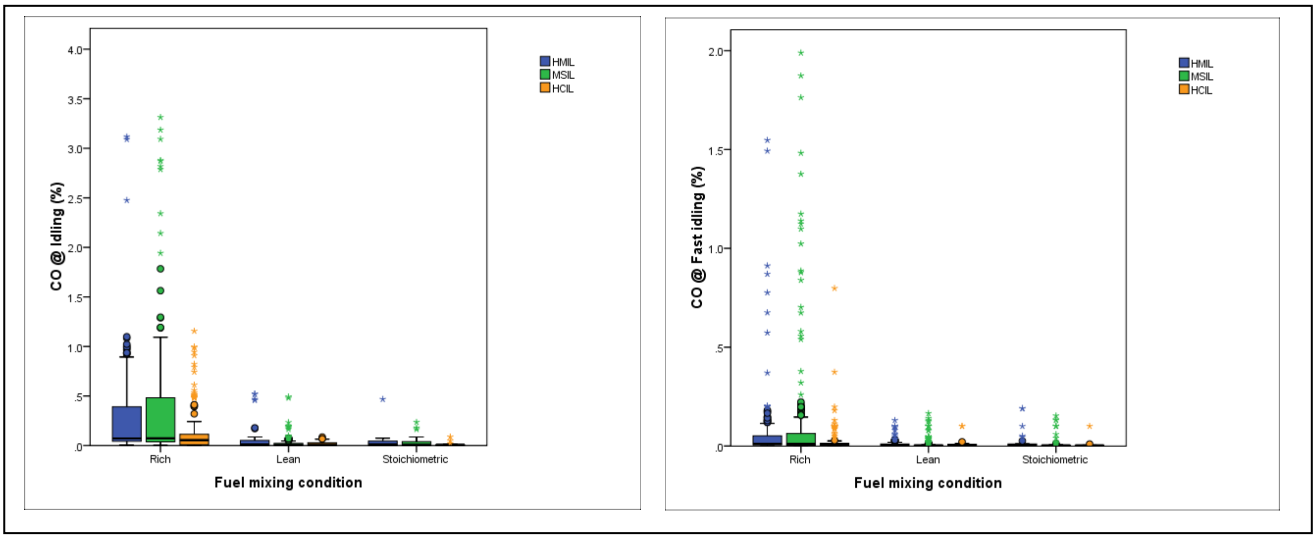


Fig. 4.225 Fuel mixing condition vs. CO emission - top 3 makes (at idling and fast idling)

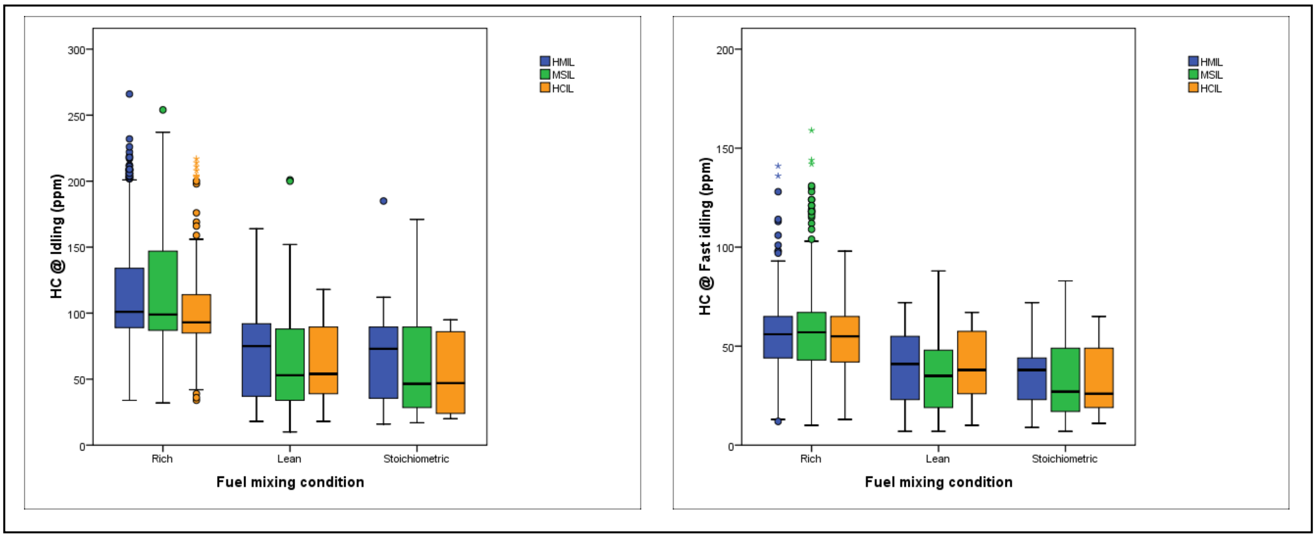


Fig. 4.226 Fuel mixing condition vs. HC emission - top 3 makes (at idling and fast idling)

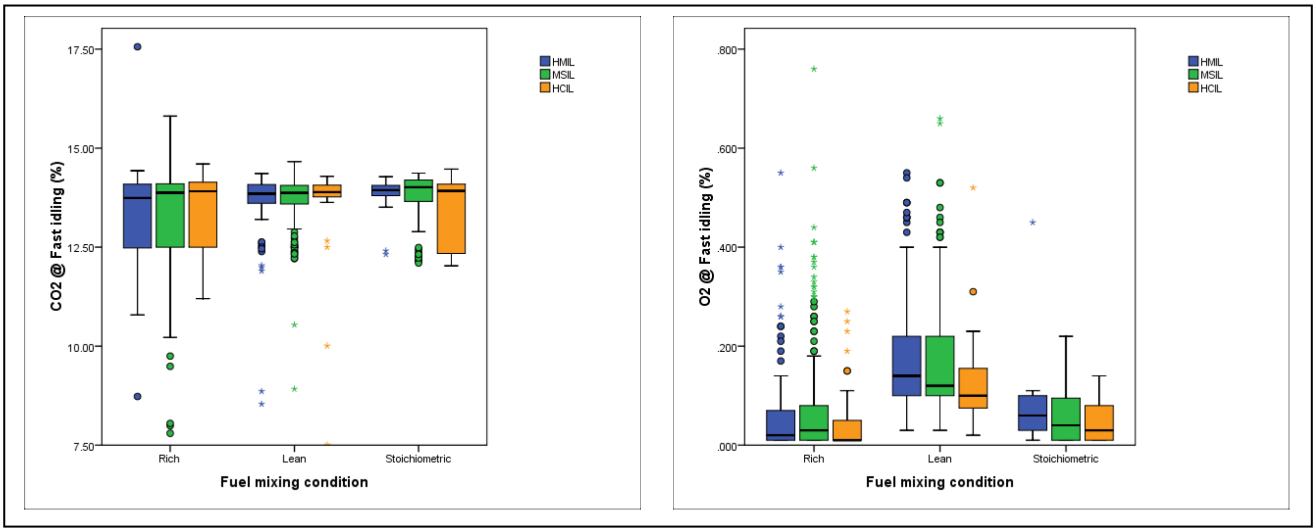


Fig. 4.227 Fuel mixing condition vs. CO_2 and O_2 emissions - top 3 makes (at fast idling)

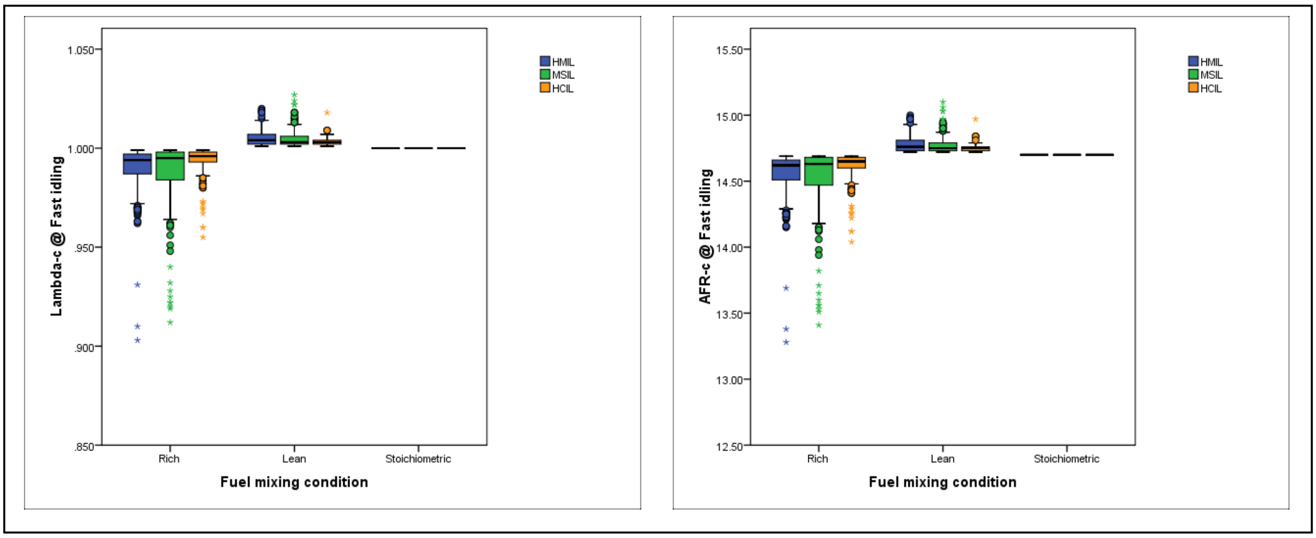


Fig. 4.228 Fuel mixing condition vs. λ and AFR - top 3 makes (at fast idling)

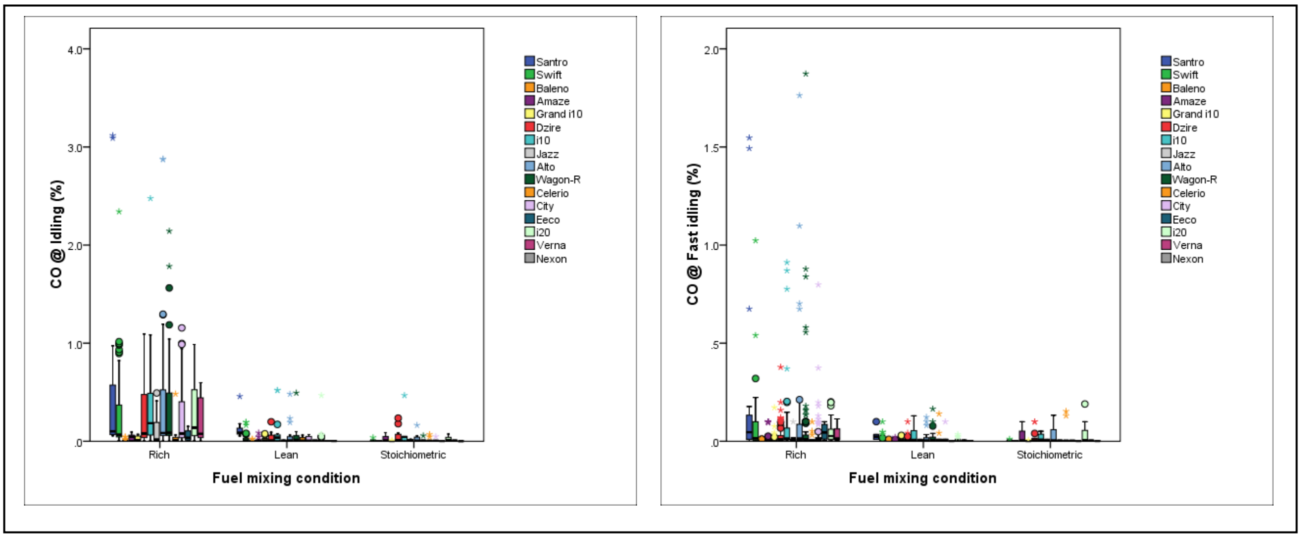


Fig. 4.229 Fuel mixing condition vs. CO emission - top 16 models (at idling and fast idling)

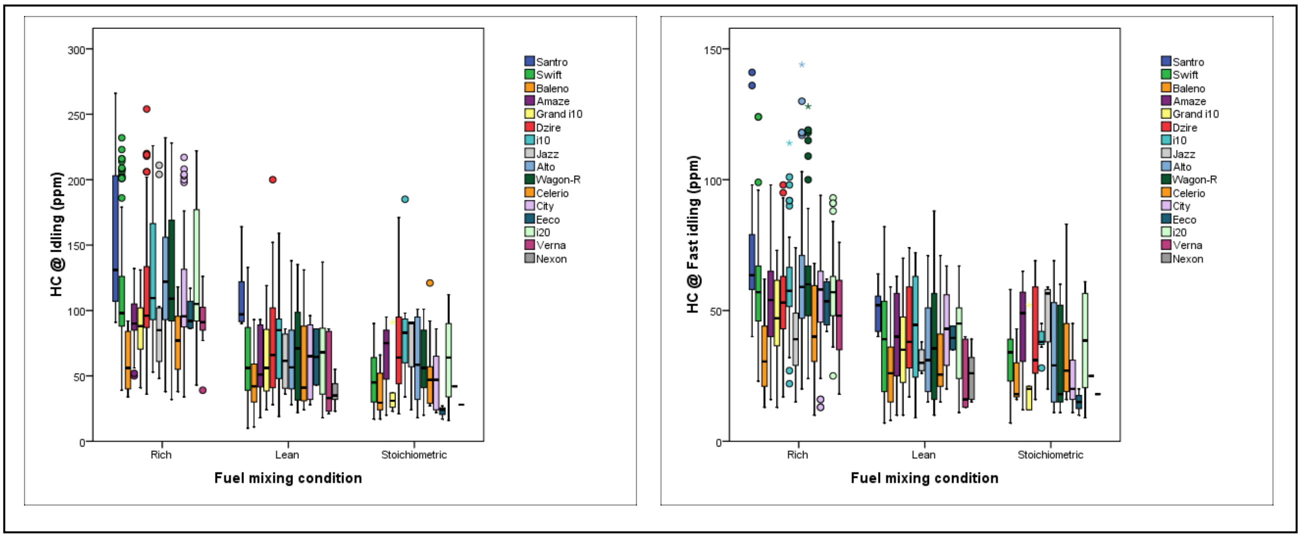


Fig. 4.230 Fuel mixing condition vs. HC emission - top 16 models (at idling and fast idling)

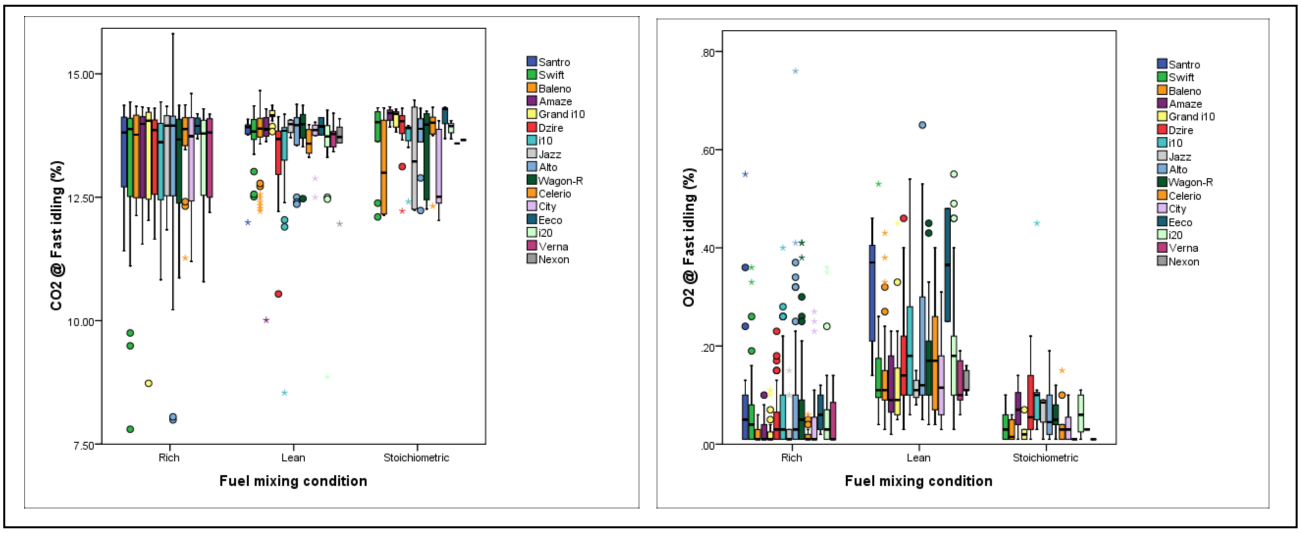


Fig. 4.231 Fuel mixing condition vs. CO_2 and O_2 emission - top 16 models (at fast idling)

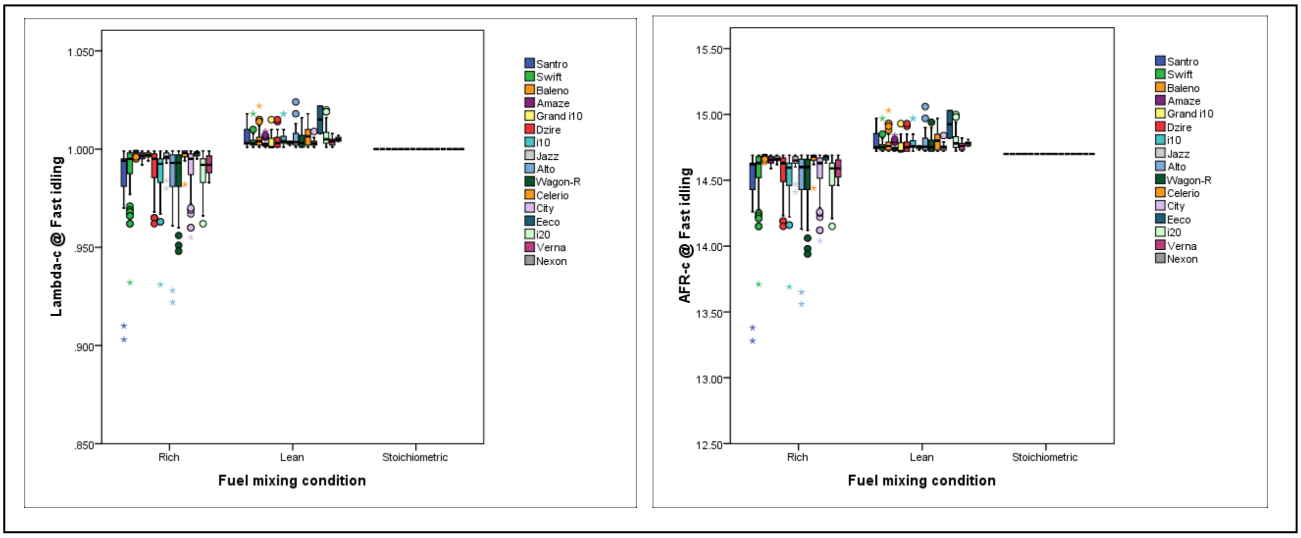


Fig. 4.232 Fuel mixing condition vs. λ and AFR - top 16 models (at fast idling)

4.1.2 Diesel-driven passenger cars

4.1.2.1 Vehicle age and mileage

The effect of vehicle age and mileage on SE (smoke emission or exhaust particles in a qualitative sense) for the entire data range in FAST mode is shown in Figure 4.232. It is revealed that the emission characteristic for both the vehicle-related parameters are best described by a 2nd order polynomial curve amid some apparent scatter in data. It was observed that both the age and mileage of the vehicles have a direct and positive correlation with the SE. Older vehicles and those having accumulated relatively higher mileage (irrespective of age) tend to emit more exhaust particles in the tailpipe and vice-versa.

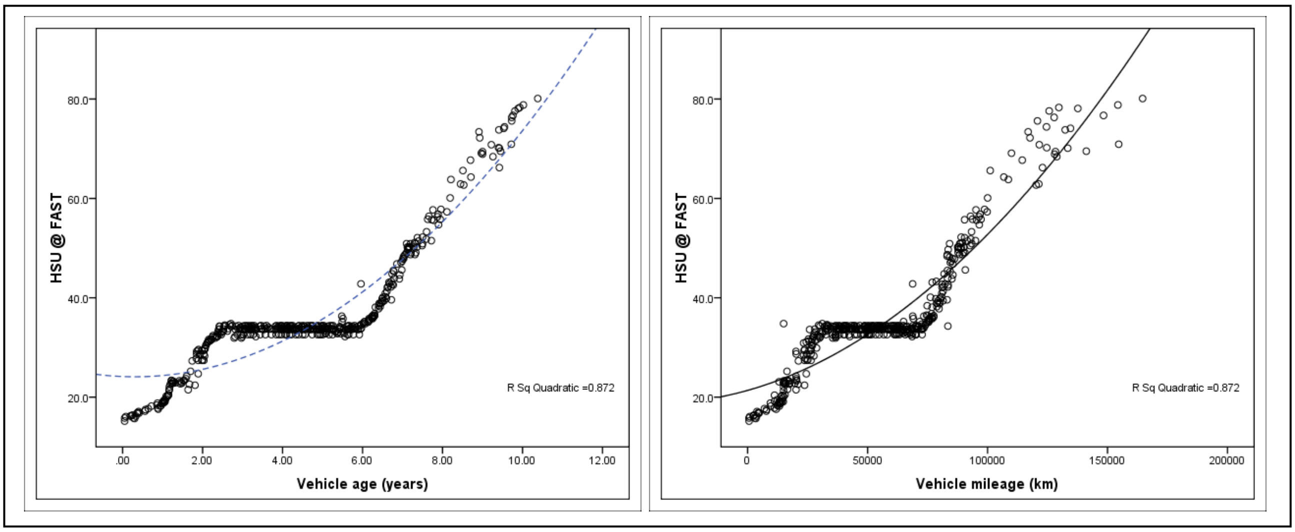


Fig. 4.233 Vehicle age and mileage vs. SE (HSU @ FAST)

The emission equations along with corresponding R^2 values computed using 2nd order polynomial curve presenting of correlation of SE with respect to vehicle age and mileage are given in Table 4.22.

Table 4.22: Emission equations with respect to vehicle age and mileage (whole dataset)

Parameter	Variable	Equation	R^2
SE (HSU @ FAST) – top 5 makes	Vehicle age	$y = 0.5274x^2 - 0.3241x + 24.15$	0.872
	Vehicle mileage	$y = 0.0000000018x^2 + 0.0001358133x + 21.3756$	0.873

The field-measured SE values in respect of vehicle age and mileage were also plotted for top 5 makes and top 13 models of diesel-powered passenger cars, based on their representativeness in the sample size and also considering the fact that none of the independent variables being tested are missed out. This make and model-wise analysis aimed at better data resolution and variability amongst makes and models apart from whole data. The scatter plots obtained from the data analysis are presented in Figures 4.234 and 4.235, respectively.

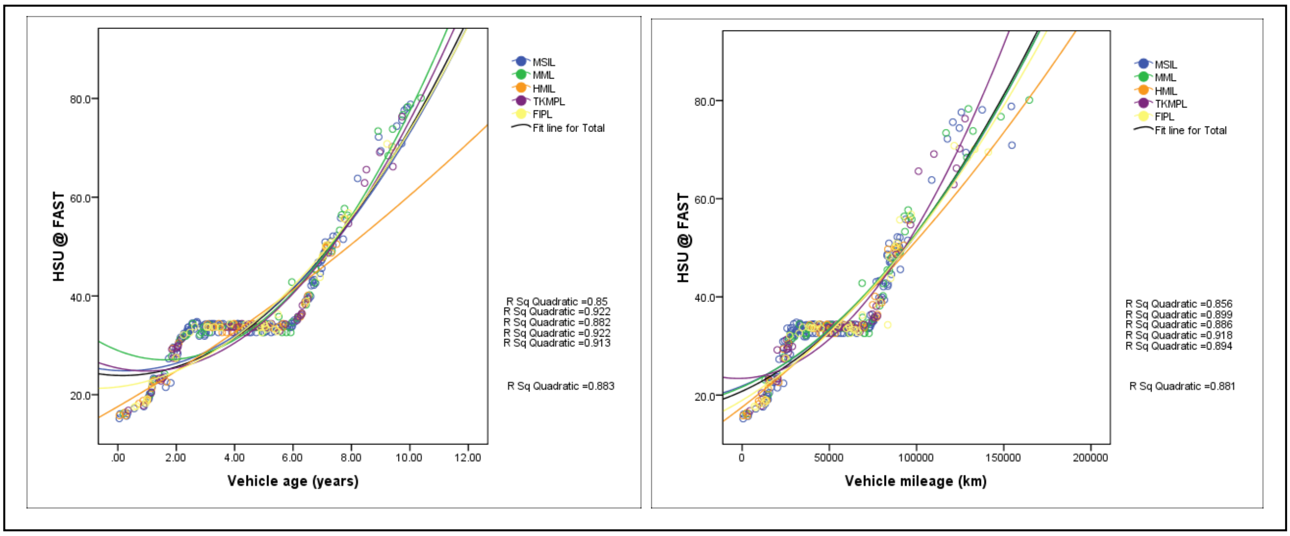


Fig. 4.234 Vehicle age and mileage vs. SE (HSU @ FAST) – top 5 makes

It is again observed that the dependence of SE on both vehicle age and mileage is polynomial or quadric in nature. The resultant emission equations and R^2 values obtained for the best-fit quadratic trendlines in case of the top 5 makes are presented in Table 4.23 and the same for the top 13 models are presented in Table 4.24 respectively. The make-wise analysis reveals that TKMPL, FPIL and MML observe the maximum correlation of SE in respect of vehicle age and mileage both, implying that cars of these makes emit the most SE upon getting older and accumulating more mileage compared to the remaining two makes, i.e., MSIL and MML.

The model-wise analysis considering the top 13 models follow the trends of correlation on the lines of the whole dataset and make-wise interpretations. Models, such as, Swift, Amaze, Verna, Fortuner, Brezza, Figo, Ciaz and Scorpio exhibit the maximum degree of correlation whereas models, namely, Duster and Ecosport report relatively poorer correlation coefficients. It is noteworthy to mention here that a larger make and model-wise dataset could relveal a furthermore insight into this dependence or correlation; however, with the entire dataset (n = 460), the dependnce of SE on age and mileage may fairly be established. Therefore, there exists a scope of refinement of such correlations for make and models both with a larger dataset.

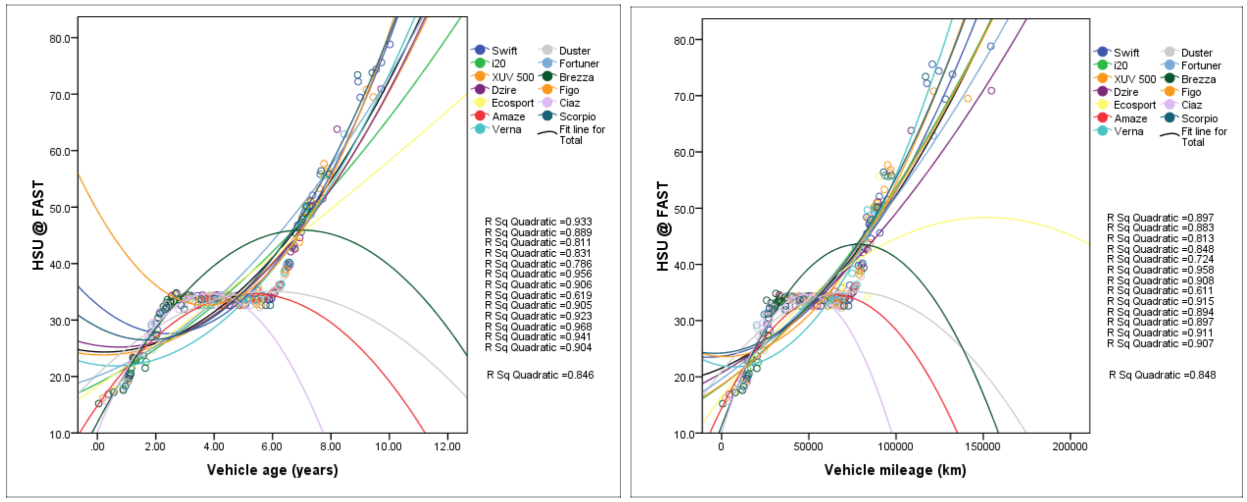


Fig. 4.235 Vehicle age and mileage vs. SE (HSU @ FAST) – top 13 models

Table 4.23: Emission equations with respect to vehicle age and mileage (top 5 makes)

Makes	**Statistical parameter**	**Vehicle age**	**Vehicle mileage**
		SE (HSU @ FAST)	
MSIL	**Equation**	$y = 0.5099x^2 - 0.2802x + 24.886$	$y = 0.0000000016x^2 + 0.0001461681x + 21.8657$
	R^2	0.851	0.856
MML	**Equation**	$y = 0.7186x^2 - 2.331x + 28.951$	$y = 0.0000000016x^2 + 0.0001578476x + 21.6565$
	R^2	0.922	0.899
HMIL	**Equation**	$y = 0.0854x^2 + 3.4274x + 17.603$	$y = 0.0000000007x^2 + 0.0002729722x + 17.5617$
	R^2	0.882	0.886
TKMPL	**Equation**	$y = 0.626x^2 - 1.2391x + 25.411$	$y = 0.0000000029x^2 + 0.0000129043x + 23.4090$
	R^2	0.922	0.918
FPIL	**Equation**	$y = 0.4487x^2 + 0.7144x + 21.578$	$y = 0.0000000012x^2 + 0.0002145745x + 18.9337$
	R^2	0.913	0.894

Table 4.24: Emission equations with respect to vehicle age and mileage (top 13 models)

Makes	Statistical parameter	Vehicle age	Vehicle mileage
		SE (HSU @ FAST)	
Swift	**Equation**	$y = 0.8994x^2 - 4.2994x + 32.747$	$y = 0.0000000025x^2 + 0.0000402704x + 23.6483$
	R^2	0.933	0.897
i20	**Equation**	$y = 0.2058x^2 + 2.6548x + 18.767$	$y = 0.0000000012x^2 + 0.0002276047x + 18.4672$
	R^2	0.889	0.883
XUV 500	**Equation**	$y = 0.4848x^2 - 0.183x + 23.823$	$y = 0.0000000032x^2 - 0.0000127335x + 23.6170$
	R^2	0.811	0.813
Dzire	**Equation**	$y = 0.5282x^2 - 0.7563x + 25.473$	$y = 0.0000000010x^2 + 0.0001834388x + 20.7039$
	R^2	0.831	0.848
EcoSport	**Equation**	$y = 0.0352x^2 + 3.6444x + 18.246$	$y = -0.0000000014x^2 + 0.0004191733x + 16.490$
	R^2	0.786	0.724
Amaze	**Equation**	$y = -0.7056x^2 + 7.4833x + 14.816$	$y = -0.0000000049x^2 + 0.0006272272x + 14.446$
	R^2	0.956	0.958
Verna	**Equation**	$y = 0.5857x^2 - 0.7025x + 22.08$	$y = 0.0000000040x^2 - 0.0000570698x + 21.9812$
	R^2	0.906	0.908
Duster	**Equation**	$y = -0.4183x^2 + 4.9608x + 20.366$	$y = -0.0000000025x^2 + 0.0003779768x + 20.973$
	R^2	0.619	0.611
Fortuner	**Equation**	$y = 0.3345x^2 + 1.9819x + 20.073$	$y = 0.0000000010x^2 + 0.0002216296x + 19.6422$
	R^2	0.905	0.915
Brezza	**Equation**	$y = -0.7015x^2 + 9.7522x + 11.835$	$y = -0.0000000052x^2 + 0.0008218589x + 11.285$
	R^2	0.923	0.894
Figo	**Equation**	$y = 1.2228x^2 - 9.0599x + 49.39$	$y = 0.0000000013x^2 + 0.0002149189x + 18.5787$
	R^2	0.968	0.897
Ciaz	**Equation**	$y = -1.6445x^2 + 12.698x + 10.158$	$y = -0.000000010x^2 + 0.001004939x + 10.1351$
	R^2	0.941	0.911
Scorpio	**Equation**	$y = 0.7865x^2 - 2.6815x + 28.755$	$y = 0.0000000029x^2 + 0.0000230945x + 24.2304$
	R^2	0.904	0.907

An insight into the plots and the emission equations’ tables also point to the comparative standing of trendlines for the top 5 makes and top 13 models of the diesel-driven passenger cars plying in the megacity of Delhi. Considering the trendlines to be the guiding factor, the relative standing of different makes and models in terms of their smoke (particle) emissions) in FAST mode due to vehicle age and mileage as independent variables, in descending order is presented in Tables 4.25 and 4.26. Makes such as, MML, TKMPL and MSIL fare better as far as the effect of age and mileage is concerned in the sense that these makes are expected to be affected most emitting more SE compared to likes of FPIL and MSIL. On the other hand, models, namely, XUV 500, Scorpio and Swift are most likely to emit more SE upon getting older and accumulating more mileage compared to models like, Amaze, Ciaz, Duster and EcoSport. This finding may be used for a more effective tuning of vehicles (particular makes and / or models) towards their environmental performance.

Table 4.25: Relative standing of different makes in descending order in terms of their SE characteristics due to age and mileage

S. No.	Effect of age on SE	Effect of mileage on SE
	HSU @ FAST	
1.	MML	TKMPL
2.	TKMPL	MSIL
3.	MSIL	MML
4.	FIPL	FIPL
5.	HMIL	HMIL

Table 4.26: Relative standing of different models in descending order in terms of their SE characteristics due to age and mileage

S. No.	Effect of age on SE	Effect of mileage on SE
	HSU @ FAST	
1.	XUV 500	Verna
2.	Scorpio	XUV 500
3.	Swift	Scorpio
4.	Verna	Swift
5.	Fortuner	i20
6.	Dzire	Figo
7.	Figo	Fortuner
8.	i20	Dzire
9.	EcoSport	EcoSport

10.	Brezza	Duster
11.	Duster	Brezza
12.	Amaze	Amaze
13.	Ciaz	Ciaz

4.1.2.2 Other vehicle-related parameters

The effect of other vehicle parameters on SE, for e.g., vehicle body type (Sedan / Hatchback / SUV); registration life half-past status (Yes / No); kerb weight, transmission type (Manual / Automatic); drivetrain type (Front / Rear / All-Wheel or 4*4); applicable emission norm during manufacturing (BS IV / BS III); maintenance category based on no. of fitness visits to manufacturer's authorized service centres (Very good / Good / Poor / Unsatisfactory) and fuel distribution system (CRDI / DI / PGM-FI) was also analyzed in the present study. The plots depending upon the variable type (numerical or string) were drawn, i.e., scatter, or boxplots in SPSS package. The analysis revealed that the vehicle variables, such as status of registration life half-past, applicable emission norm (while the vehicle was manufactured to comply to the relevant and extant emission norm, just came out of plant and got registered as light motor vehicle for private operation), and vehicle maintenance category were found to affect the smoke emission from the diesel-driven passenger cars.

Cars with registration life half-passed were found to emit more SE compared to those yet to complete the half-life of registration (i.e., five years from the date of first registration at RTO – Regional Transport Office). The outliers in both registration life categories were also consistent with this finding (Fig. 4.236). The make and model-wise plots followed the pattern, i.e., makes and models having passed their half of registration lives emitted more compared to other ones.

All makes and models (not having passed their half the registration life) were found to be compliant to extant in-use PUC certification norm of 65 HSUs whereas makes, such as, TKMPL and MML and models, such as, Verna, Swift, XUV 500 and Brezza were found to be emitting in excess of the norm having gone beyond the registration life benchmark (Figs. 4.237 and 4.238).

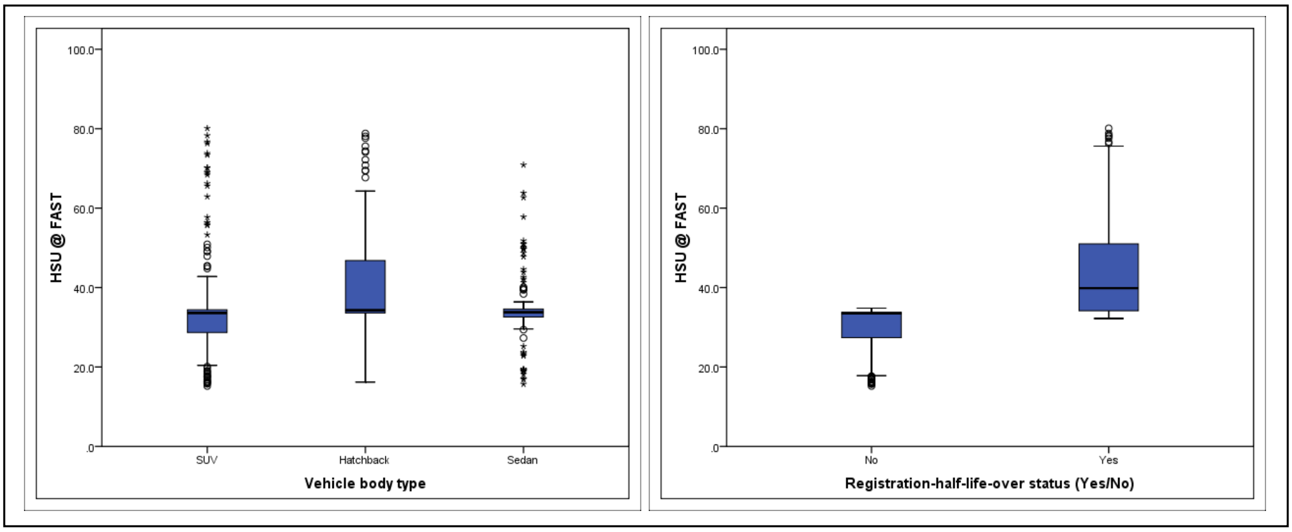


Fig. 4.236 Vehicle body type and registration life status vs. SE (HSU @ FAST)

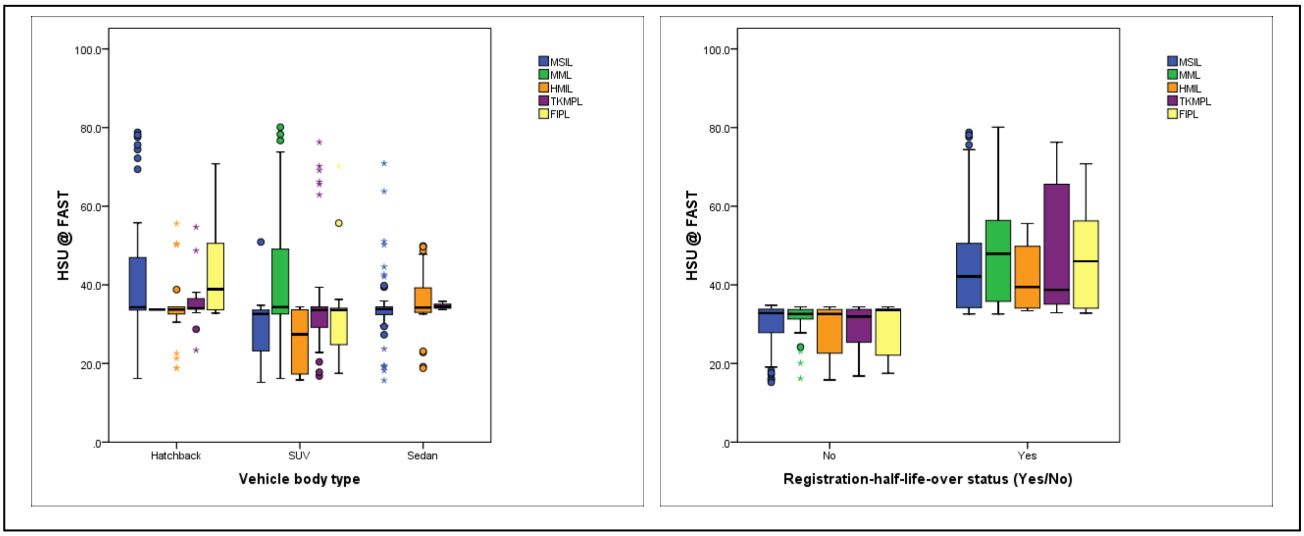


Fig. 4.237 Vehicle body type and registration life status vs. SE (HSU @ FAST) - top 5 makes

Emission norm at (during) manufacturing has a direct influence on SE values. Vehicles manufactured to comply with a more stringent emission norm (the newer norm in other words) emit less SE compared to those which were manufactured to be compliant to an older (outgoing) emission norm. For e.g., BS IV-compliant vehicles usually emit lesser amount of SE while remaining compliant to BS IV (i.e., emitting below the cut-off value of emission as 50 HSU) except for a few rare cases needing to undergo a thorough maintenance check. On the other hand, BS III-compliant vehicles were almost always non-compliant to BS IV emitting more than 50 HSU or even non-compliant to itself or in-use emission norm of 65 HSU in most of the cases (Fig. 4.242).

Make and model-wise plots exhibited a similar trend as of the whole dataset. Only MML and MSIL have BS III-compliant cars plying on the city roads having the maximum range of HSU (including outliers); however, both report a remarkable reduction in SE / HSU values for its cars complying with BS IV norms. TKMPL, FIPL and HMIL follow closely (Fig. 4.243). Model-wise speaking, Swift and XUV 500 are the only cars to have featured in the list of BS III-compliant diesel vehicles and more so with the highest range of HSU (> 65 HSU in all cases). All other models were BS IV-compliant although with a significant number of non-compliant cars mostly from XUV 500, Brezza, i20, Scorpio in descending order having EcoSport, Brezza, Fortuner and Ciaz as the lowest emitting cars (Fig. 4.244).

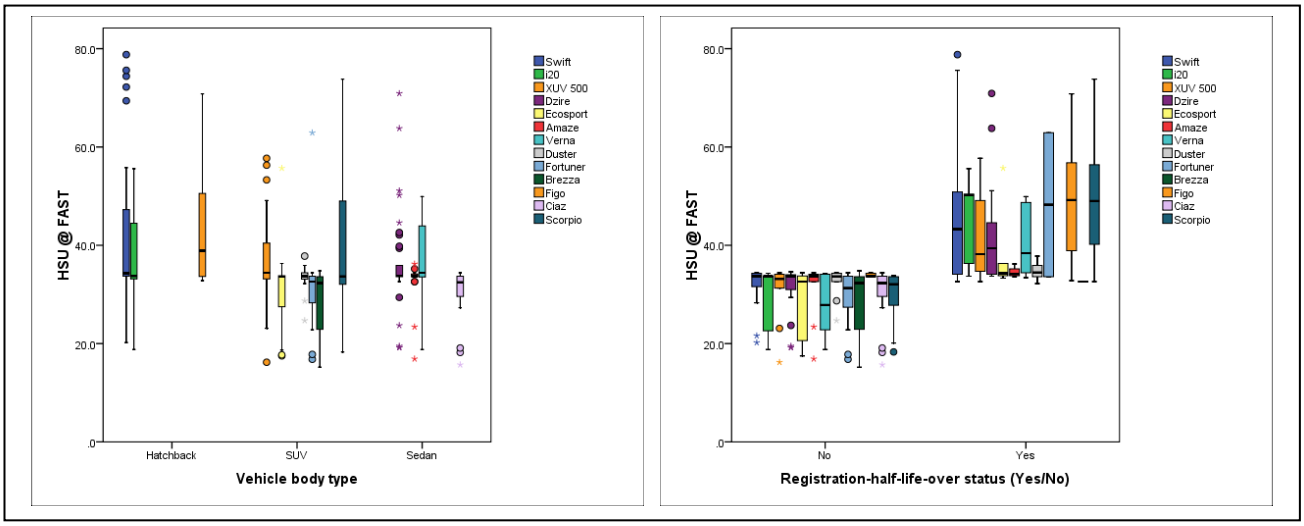


Fig. 4.238 Vehicle body type and registration life status vs. SE (HSU @ FAST) - top 13 models

The effect of the vehicle variable 'maintenance category' was also evaluated for its effect on diesel car's smoke emission. The criteria to categorize vehicles based on their number of I/M visits paid to the respective authorized service centres for periodic / casual fitness check over the last two years was used for diesel-driven passenger cars as well (Table 4.21). Make and model-wise plots exhibited a similar trend as of the whole dataset. It was found that the maintenance frequency of the vehicles was directly and negatively correlated to qualitative particle emission. Vehicles with a smaller number of visits for periodic or casual inspection, tuning or maintenance had a higher degree of emission compared to those maintaining a good visit record.

‘Unsatisfactory’ category of vehicles was the worst performer having the highest range of SE while the ‘Very good’ category of cars reported the best performance towards compliance, emitting SE always lower than prescribed emission limits (Fig. 4.245).

Make and model-wise analysis reported a similar trend. MSIL and MML had the maximum SE range for their ‘unsatisfactory’ category cars and the minimum emission range for their ‘very good’ maintenance category cars. All other makes fared in between depending upon their category of maintenance (Fig. 4.246). Fig. 4.247 depicted the model-wise scenario showing that the models belonging to ‘very good’ category had the minimum SE values and vice-versa. Swift, Dzire, XUV 500 and Brezza were the worst performing cars belonging to the ‘unsatisfactory’ category of maintenance and exhibited the lowest emission ranges when the category changed to ‘very good’ (Fig. 4.247).

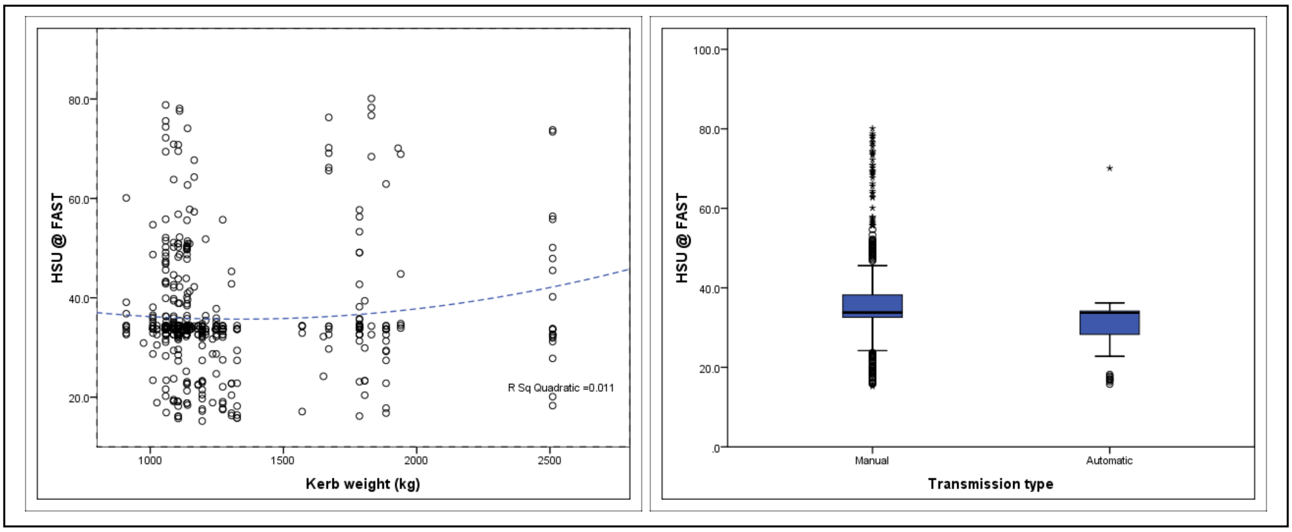


Fig. 4.239 Kerb weight and transmission type vs. SE (HSU @ FAST)

The study of diesel cars further reported that the vehicle parameters, for e.g., vehicle body type, kerb weight, transmission type, drivetrain type and fuel distribution did not seem to affect the emission from diesel cars. Make and model-wise analysis also reported a similar trend. Although outliers are apparent in the plots, it is expected that even a larger dataset in the case of makes and models will not bring about any significantly different results (Figs. 4.236 – 4.247).

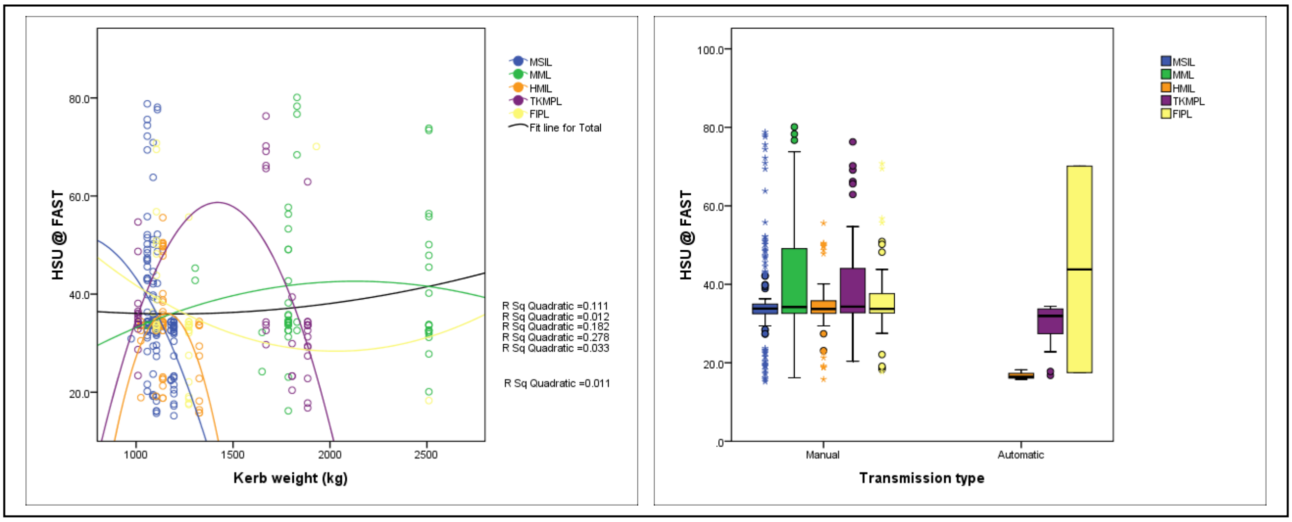


Fig. 4.240 Kerb weight and transmission type vs. SE (HSU @ FAST) - top 5 makes)

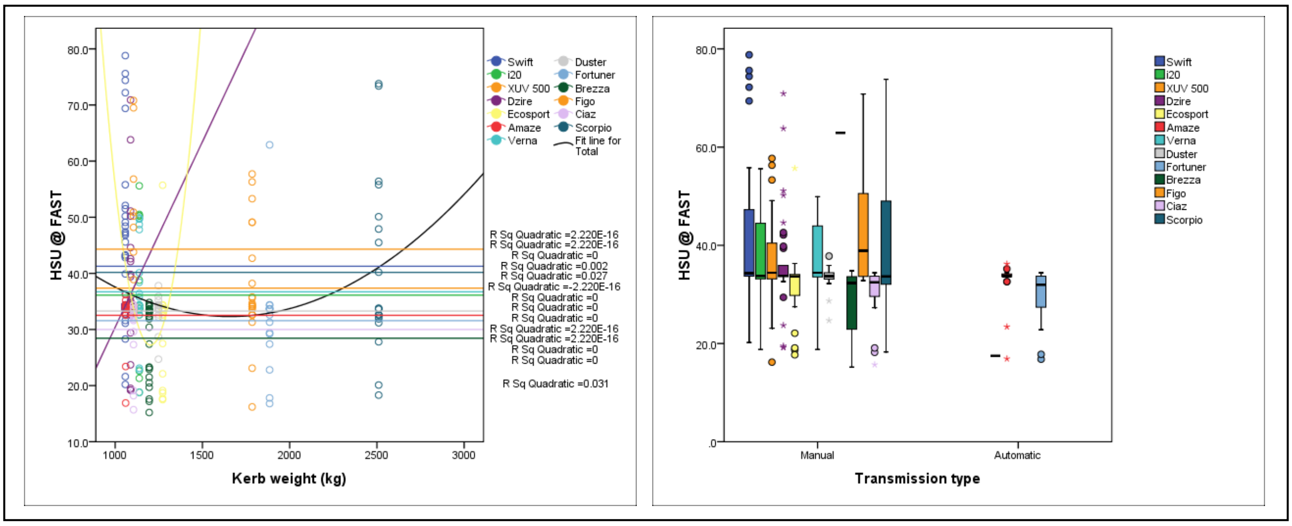


Fig. 4.241 Kerb weight and transmission type vs. SE (HSU @ FAST) - top 13 models

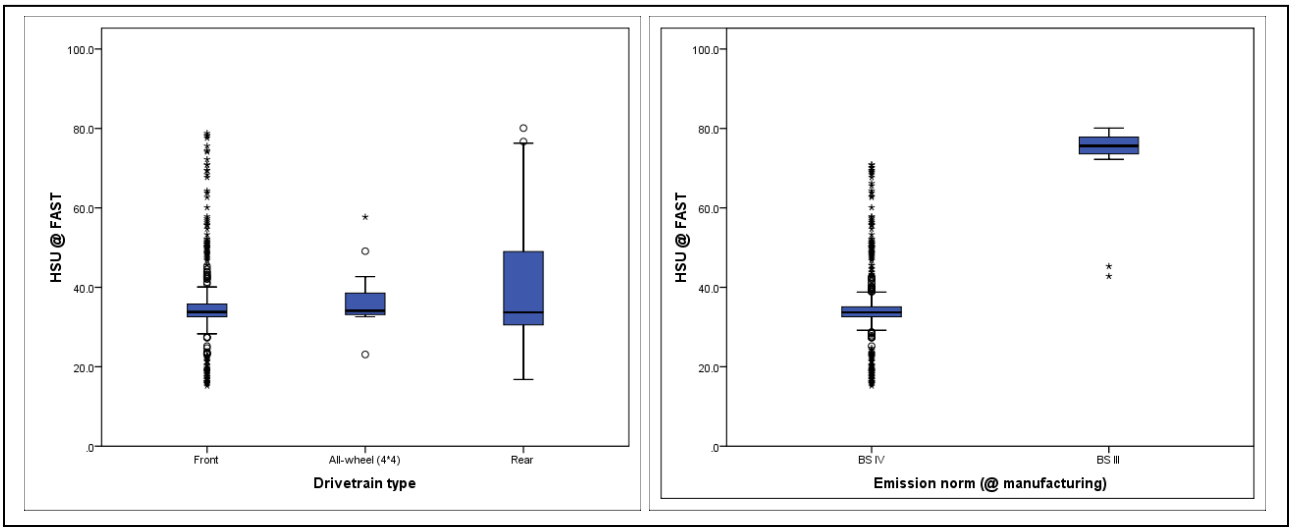


Fig. 4.242 Drivetrain and emission norm (@ mfg.) vs. SE (HSU @ FAST)

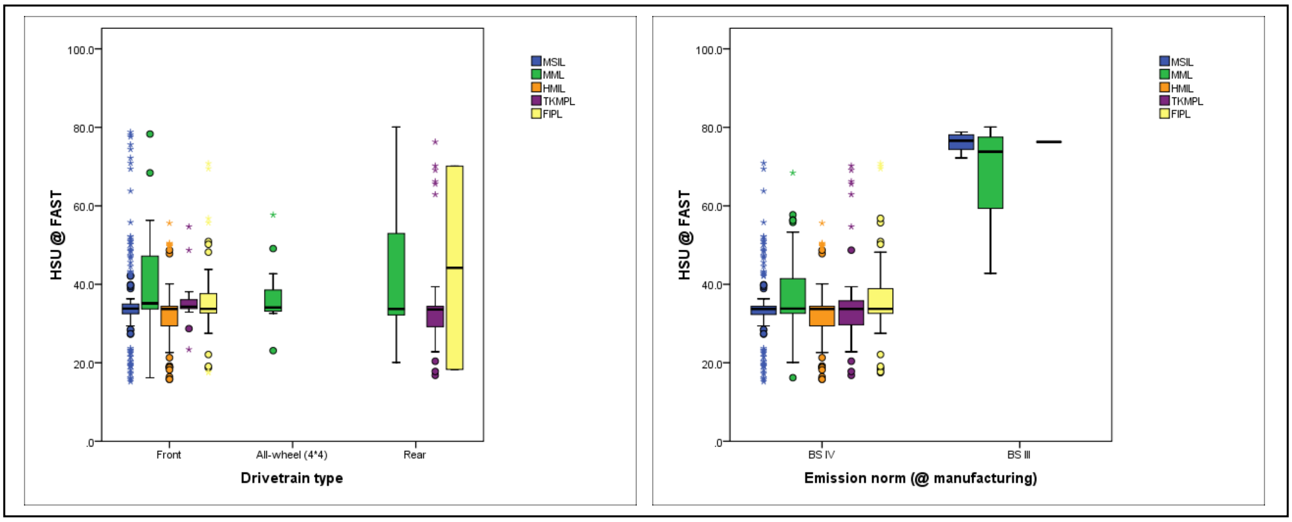


Fig. 4.243 Drivetrain and emission norm (@ mfg.) vs. SE (HSU @ FAST) - top 5 makes

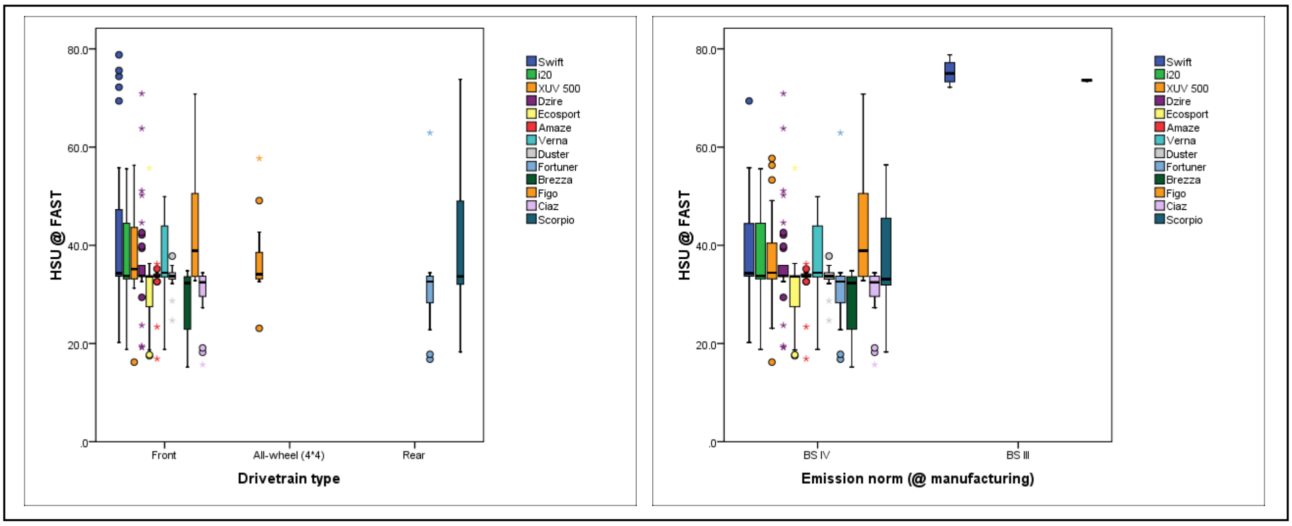


Fig. 4.244 Drivetrain and emission norm (@ mfg.) vs. SE (HSU @ FAST) - top 13 models

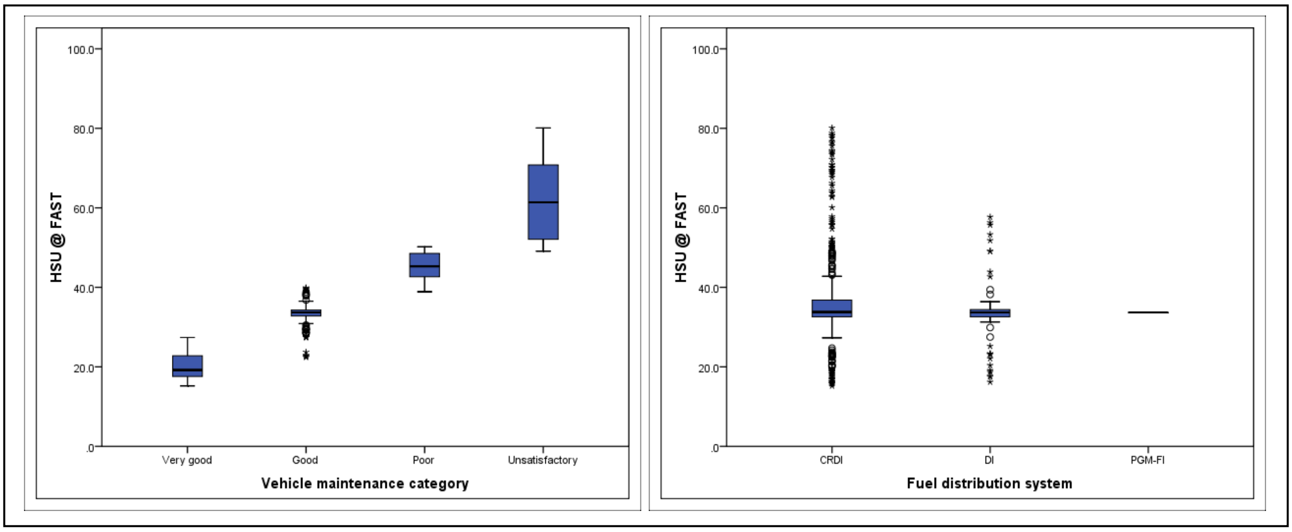


Fig. 4.245 Maintenance category and fuel distribution vs. SE (HSU @ FAST)

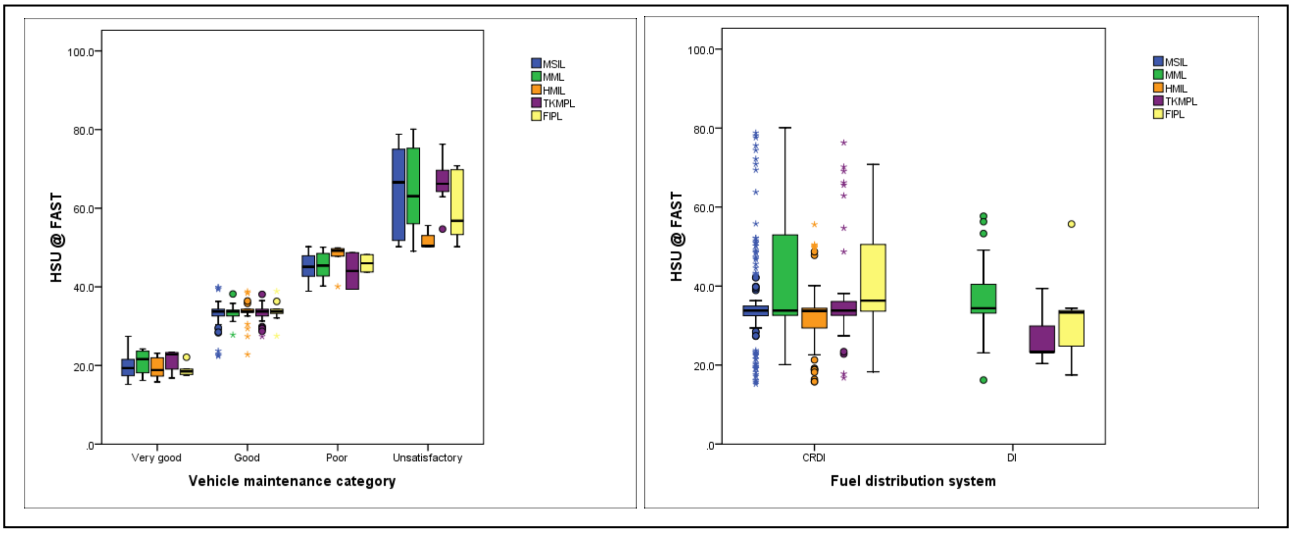


Fig. 4.246 Maintenance category and fuel distribution vs. SE (HSU @ FAST) - top 5 makes

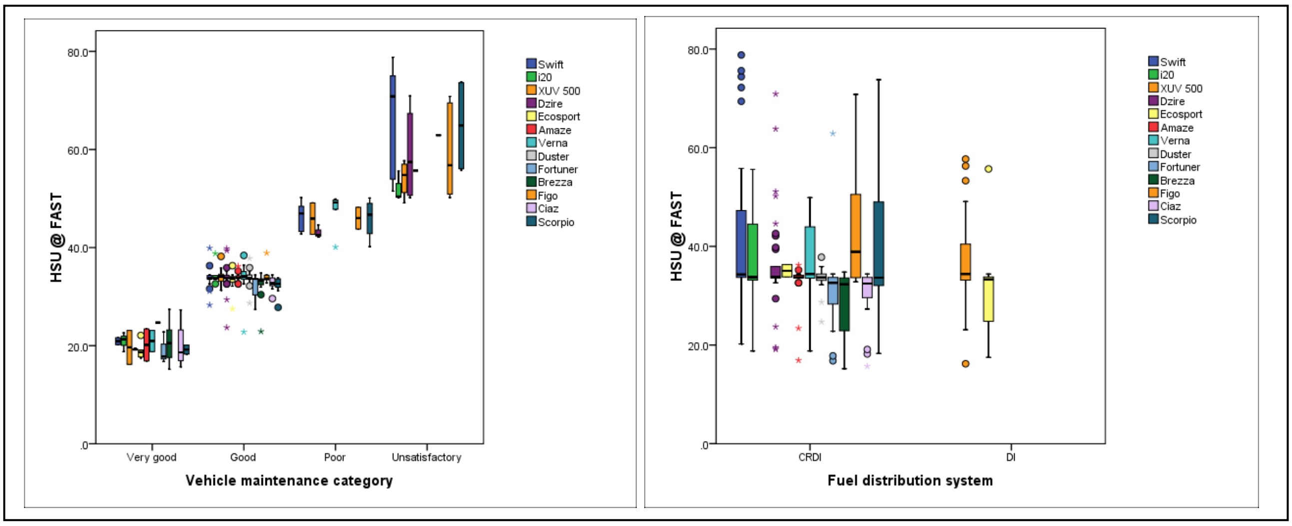


Fig. 4.247 Maintenance category and fuel distribution vs. SE (HSU @ FAST) - top 13 models

4.1.2.3 Engine-related parameters

The study also investigated the effect(s) of different engine-related aspects recorded during the emission testing programs in the NCT of Delhi, such as, Engine capacity (cc), Maximum power (bhp), Maximum torque (Nm), Compression ratio (:1), Cylinder bore (mm) and piston stroke (mm), Engine aspiration type (Natural or Turbo-charged), Number of cylinders, Number of valves per cylinder, Valve configuration (SOHC – Single overhead cam or DOHC – Double overhead cam).

The variables were analyzed using scatter plots (having continuous variables for vehicles / cases, e.g., engine capacity, maximum power, maximum torque, compression ratio, cylinder bore and piston stroke) and checked for R^2 values yielded by quadratic trendlines in order to explore correlation, if any. Boxplots were drawn for string variables at nominal scale for cases like number of cylinders, number of valves per cylinder, engine aspiration and valve configuration) and assessed for any specific pattern of change in measured values of dependent variables' ranges with respect to said engine variables.

It was found that engine variables, namely, engine capacity, maximum power, maximum torque, cylinder bore and piston stroke, number of cylinders, number of valves per cylinder and valve configuration do not seem to be related to tailpipe emission (measured in HSU terms) across all dataset scenarios, i.e., entire, top 5 makes and top 13 models.

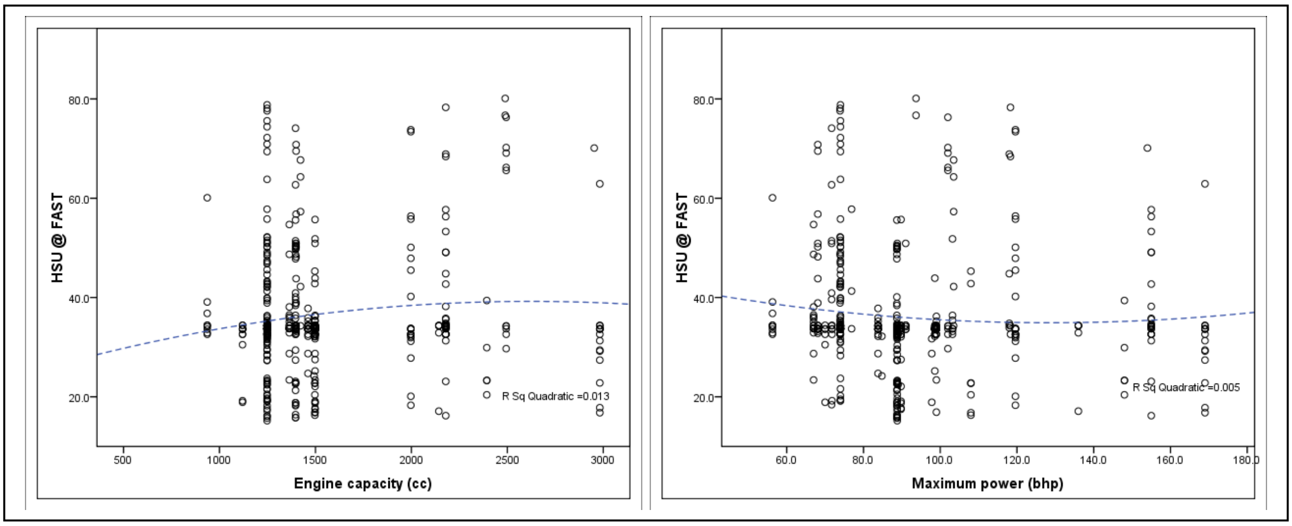


Fig. 4.248 Engine capacity and maximum power vs. SE (HSU @ FAST)

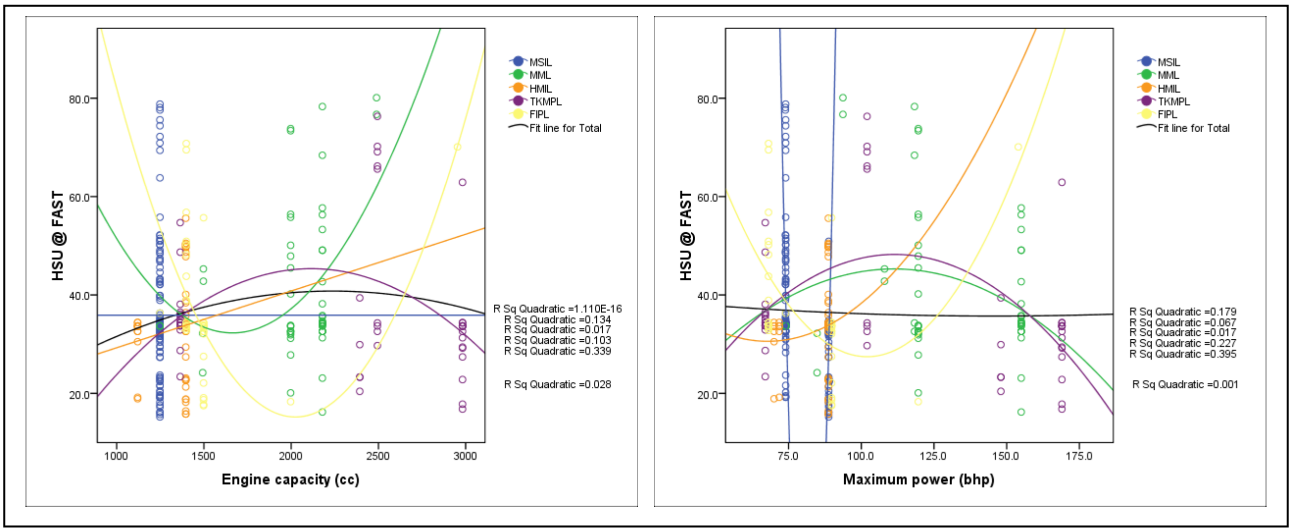


Fig. 4.249 Engine capacity and maximum power vs. SE (HSU @ FAST) - top 5 makes

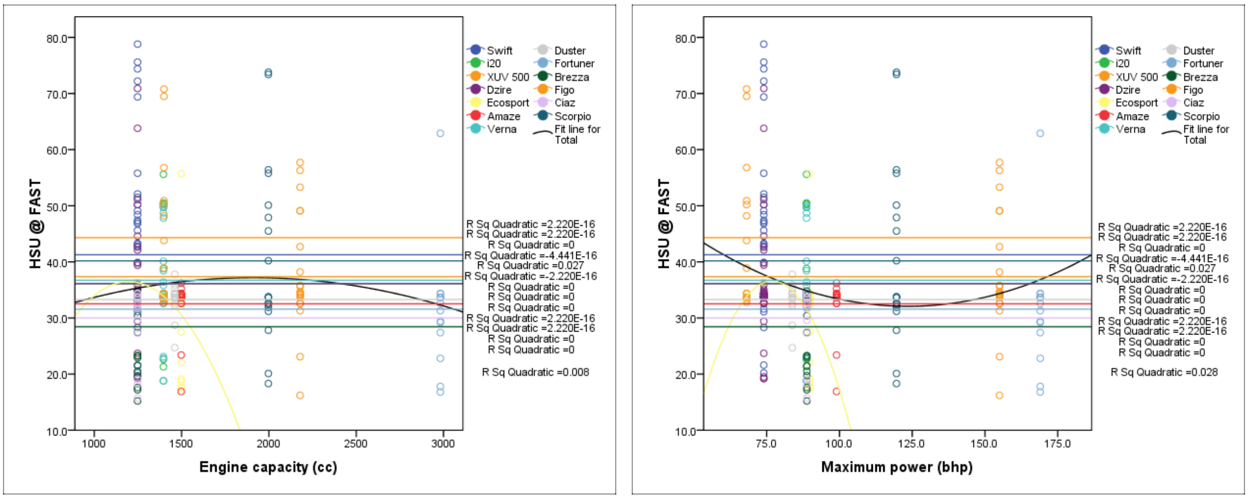


Fig. 4.250 Engine capacity and maximum power vs. SE (HSU @ FAST) - top 13 models

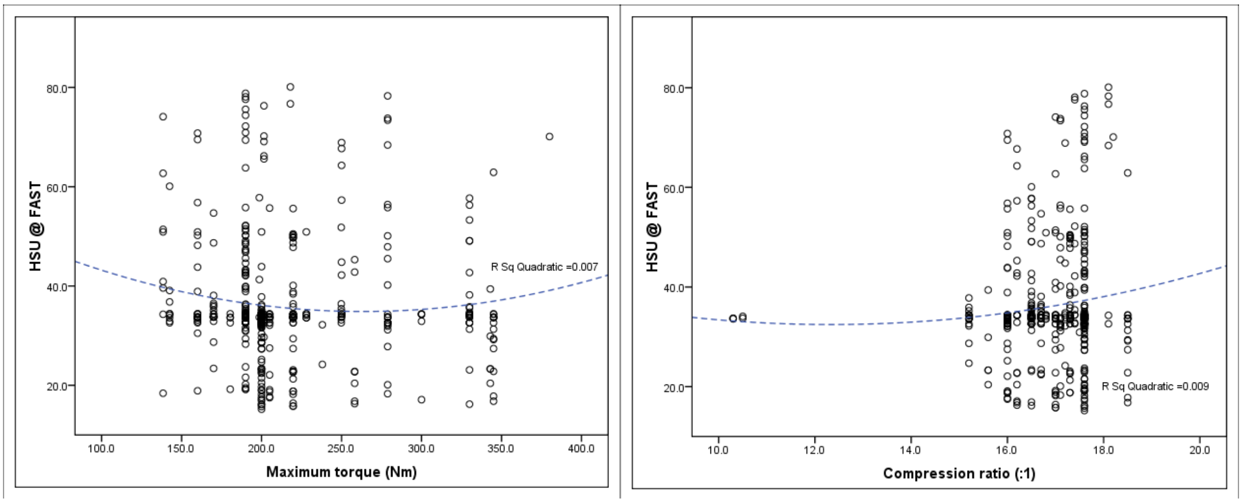


Fig. 4.251 Maximum torque and compression ratio vs. SE (HSU @ FAST)

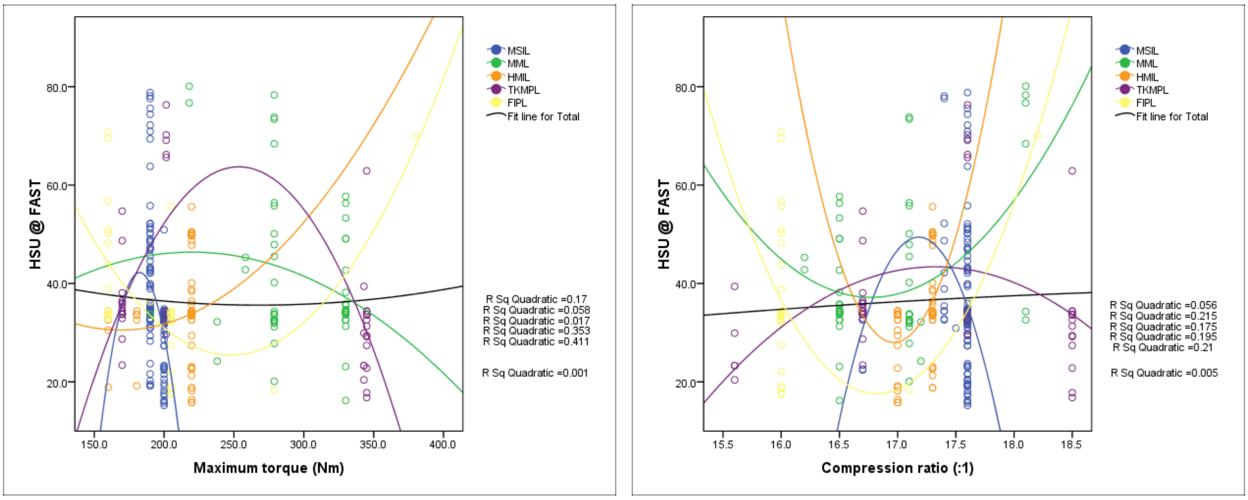


Fig. 4.252 Maximum torque and compression ratio vs. SE (HSU @ FAST) - top 5 makes

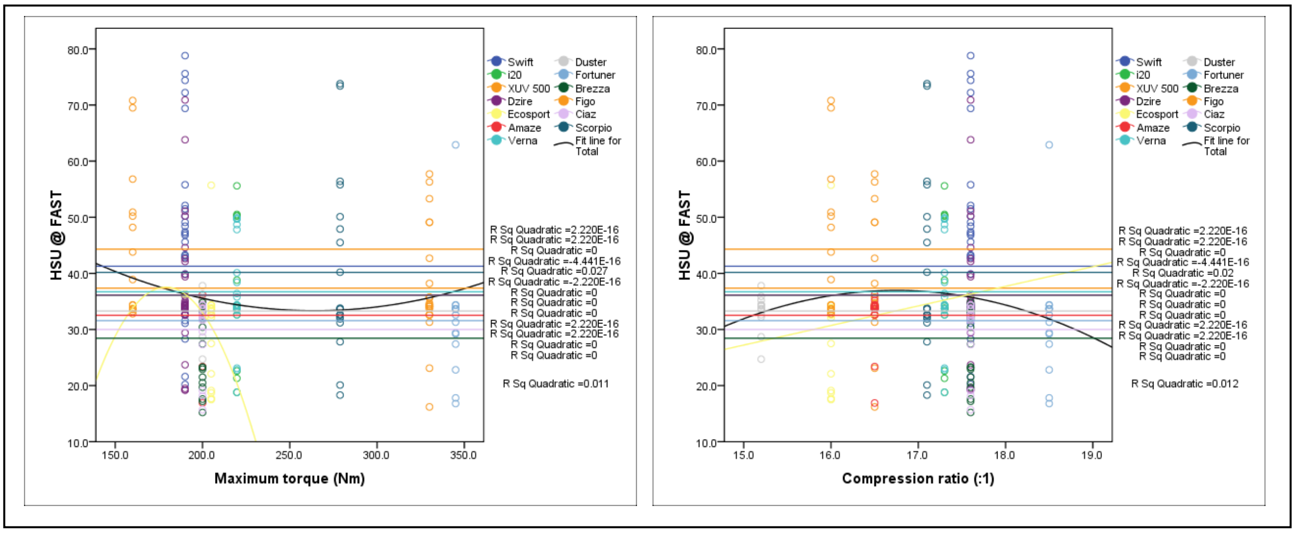


Fig. 4.253 Maximum torque and compression ratio vs. SE (HSU @ FAST) - top 13 models

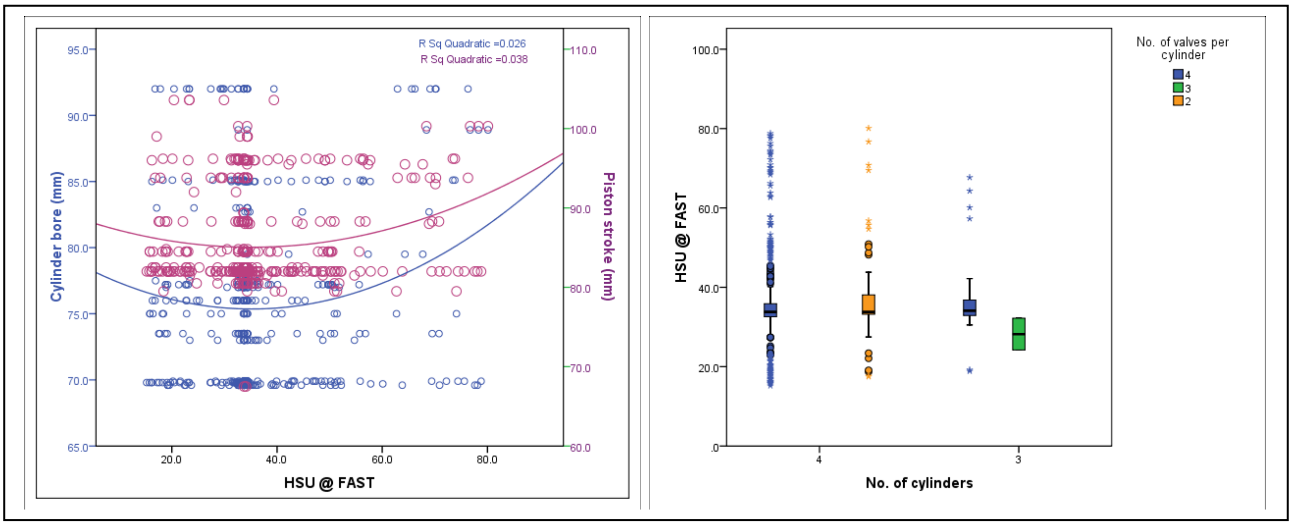


Fig. 4.254 Bore and stroke and no. of cylinders and valves vs. SE (HSU @ FAST)

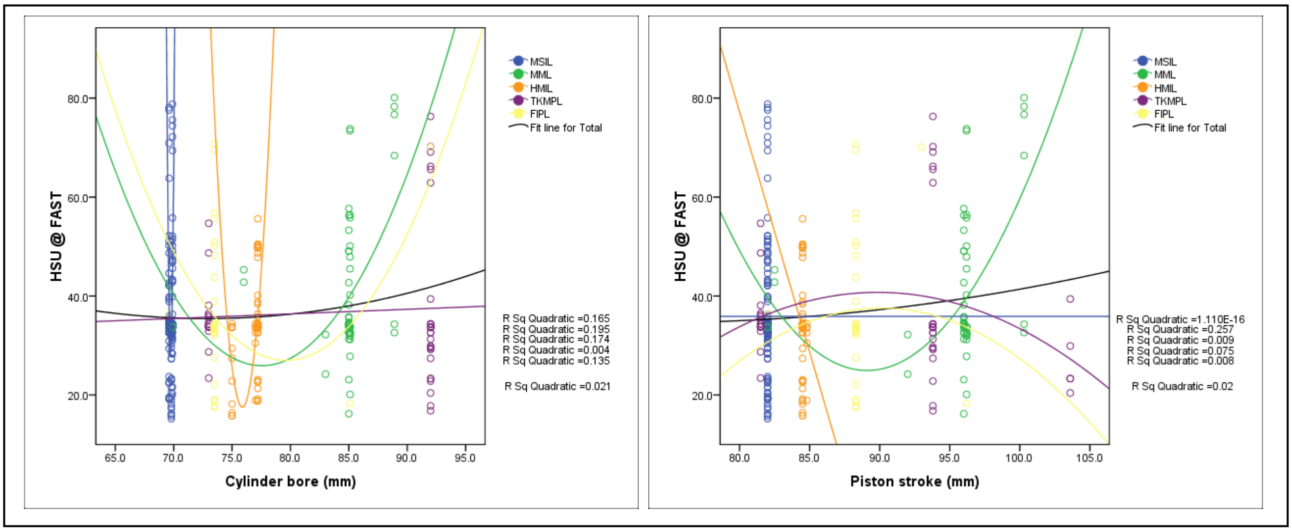


Fig. 4.255 Bore and stroke vs. SE (HSU @ FAST) - top 5 makes

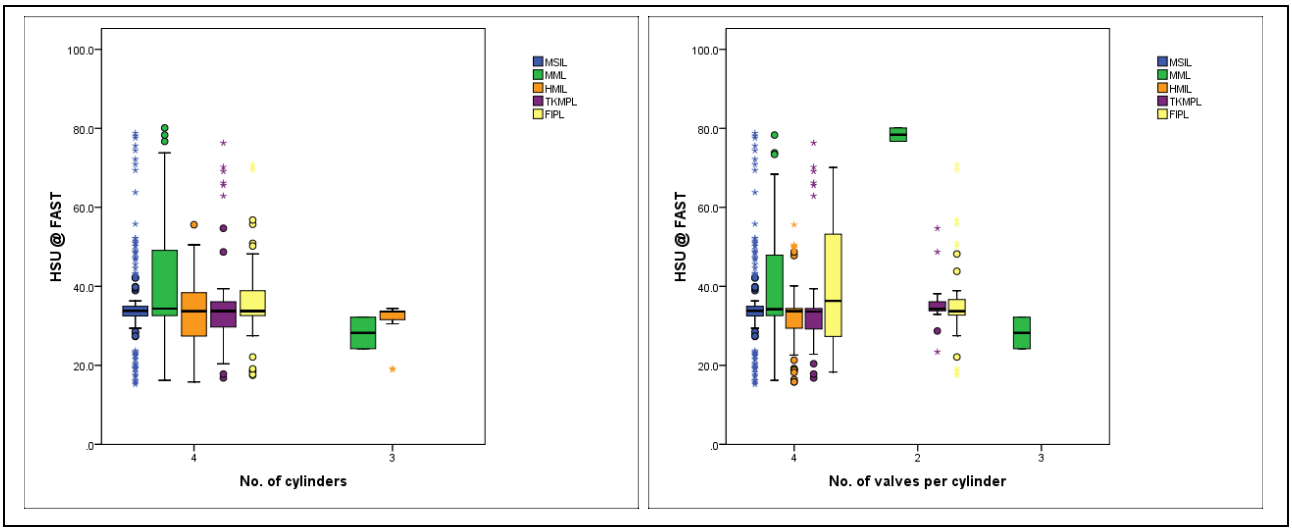


Fig. 4.256 No. of cylinders and no. of valves vs. SE (HSU @ FAST) - top 5 makes

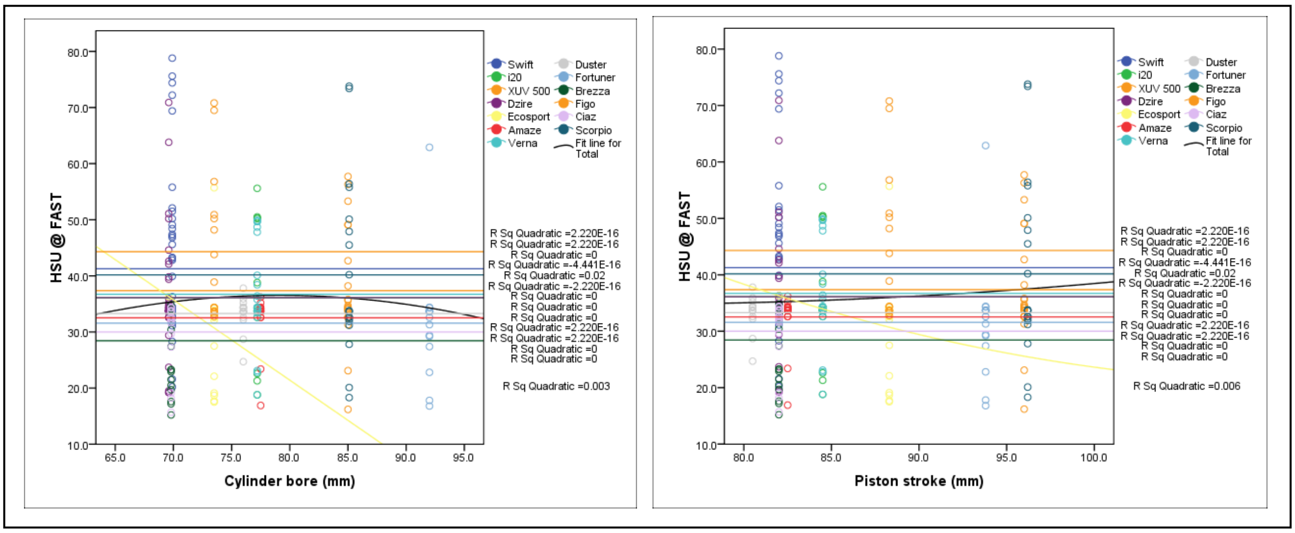


Fig. 4.257 Bore and stroke vs. SE (HSU @ FAST) - top 13 models

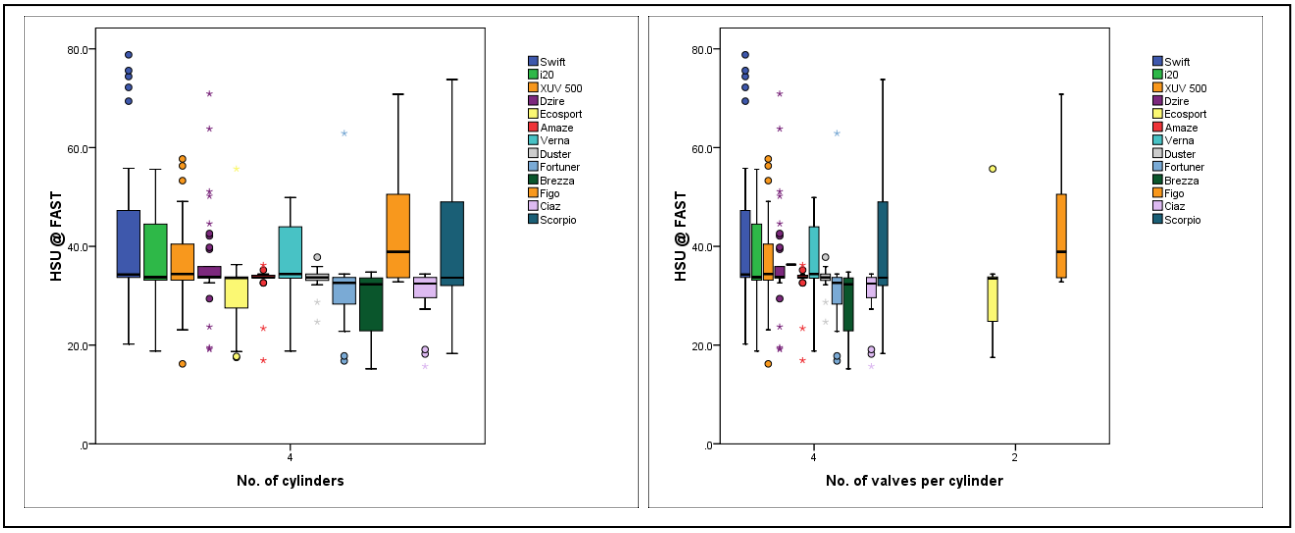


Fig. 4.258 No. of cylinders and no. of valves vs. SE (HSU @ FAST) - top 13 models

Only engine aspiration parameter was observed to influence the SE, similar to the trend observed in the case of petrol-driven passenger cars fitted with turbo-charging or having natural aspiration. While most of the petrol cars had natural aspiration compared to turbo-charging, the case of diesel-driven vehicles was different having most of the cars fitted with turbo-charging aspiration system with a handful of cars possessing natural aspiration system thanks to the technological advancement in engine technology. It was observed that engines having turbo-charging technology generally had a lower range of SE in comparison to naturally aspirated engines. Although, a high degree of outliers in datapoints related to turbo-charging is of concern; however, it may indicate to the maintenance requirement of the turbo-charging system (Fig. 4.259).

Similar trend was observed in the case of make-wise scenario i.e., makes fitted with turbo-charging, generally had a lower range of Smoke values emitted in the tailpipe and the maximum variation in the case of the two different aspiration technologies was seen in case of MML make (Fig. 4.260). On the other hand, the model-wise scenario depicted a rather different plot with Swift, XUV 500 and Scorpio emitting almost the same amount of SE in turbo-charging case as of naturally aspirated engines while all other models showed a significantly lower range of SE in the former case (Fig. 4.261).

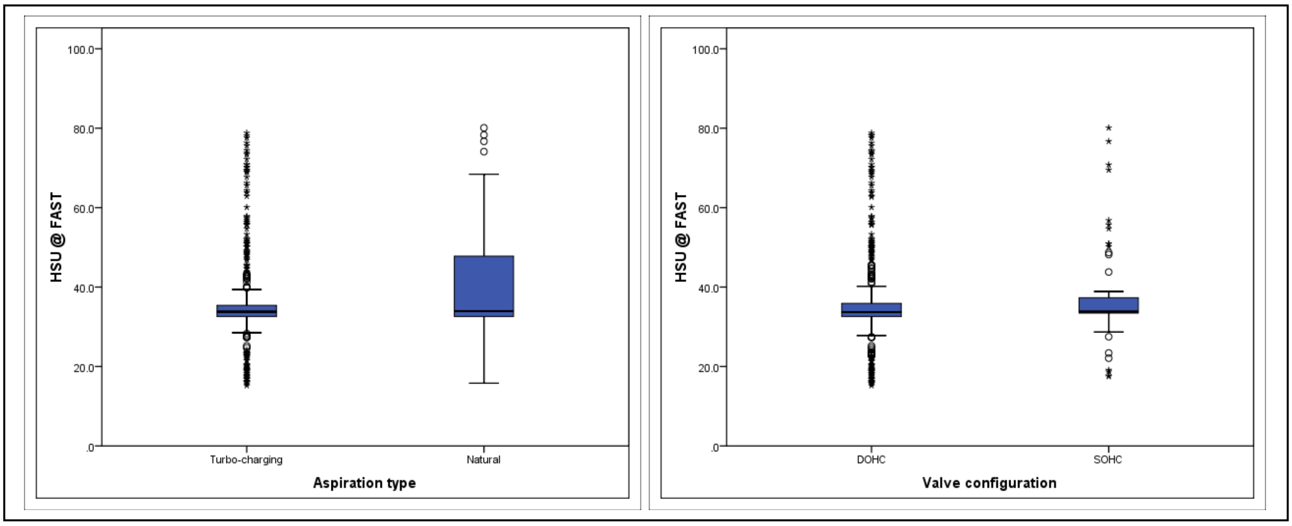


Fig. 4.259 Aspiration type and valve configuration vs. SE (HSU @ FAST)

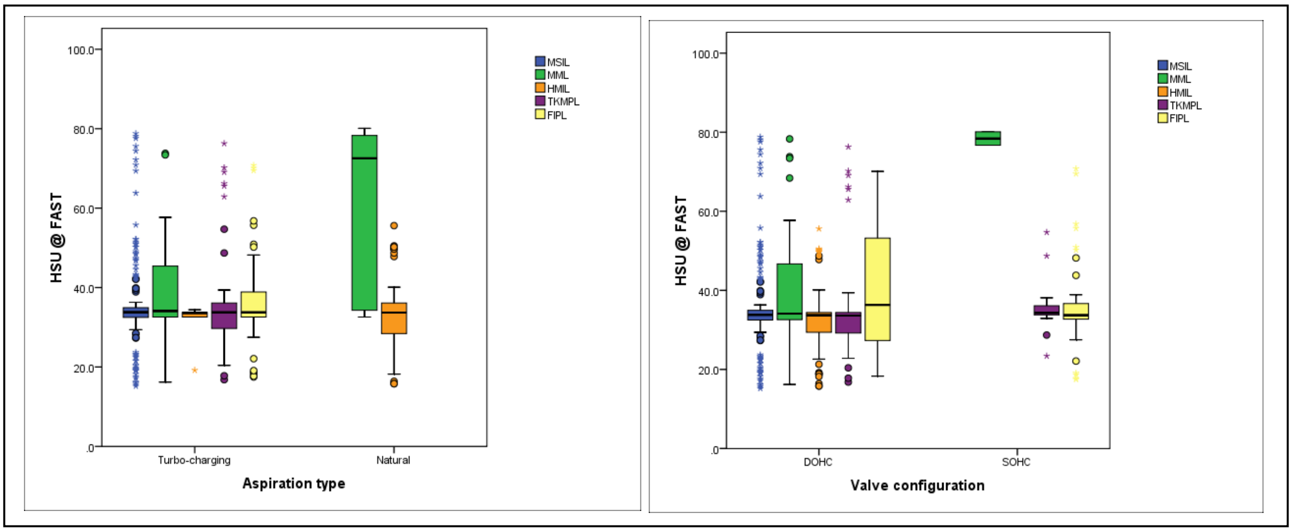


Fig. 4.260 Aspiration type and valve configuration vs. SE (HSU @ FAST) - top 5 makes

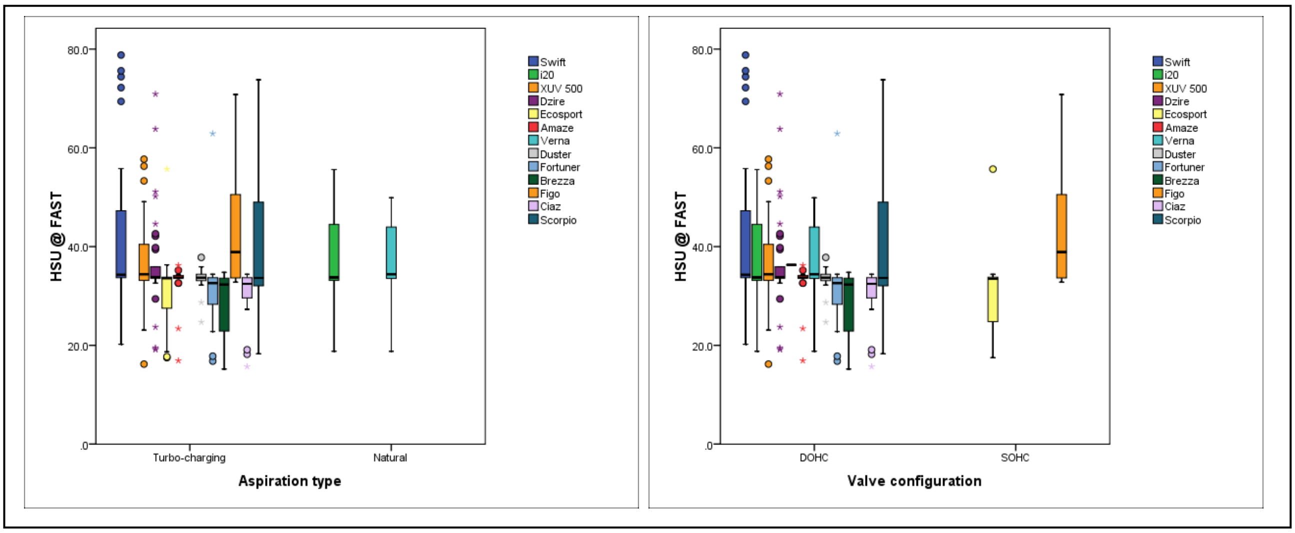


Fig. 4.261 Aspiration type and valve configuration vs. SE (HSU @ FAST) - top 13 models

4.2 Compliance with the emission norms

The compliance status to emission norms, in terms of the percentage (% age) of the total number of petrol and diesel-driven passenger cars vehicles that underwent this study for different datasets was also chalked out. All three dataset scenarios were used, i.e., entire, top 3 makes and top 16 models for petrol-driven passenger cars and entire, top 5 makes and top 13 models for diesel-driven passenger cars respectively. The compliance levels were checked for two Indian emission norms, such as BS II and BS IV (in-use) for petrol cars and BS III and BS IV for diesel cars. In line with the emission standards, petrol cars were assessed for compliance to CO in both idling and fast idling conditions (BS IV); CO only in idling mode (BS II) and HC also only in idling mode (BS IV). On the other hand, diesel cars were analyzed for their compliance levels for some emission (SE) in terms of HSU in FAST mode (for both BS III and BS IV norms) – Table 4.27.

Table 4.27: Tailpipe emission norms used in the present study for vehicle's compliance

Petrol-driven passenger cars (PDPCs)			
Emission norm	**CO @ Idling (%)**	**CO @ Fast idling (%)**	**HC @ Idling (ppm)**
BS IV	0.3	0.2	200
BS II	0.5	Not defined	
Diesel-driven passenger cars (DDPCs)			
Emission norm	**SE (HSU @ FAST)**		
BS IV	50		
BS III	65		

All dataset scenarios of petrol cars depicted very high levels of compliance towards BS IV norm (the latest and the most stringent at the time of the present tailpipe emission testing program) and even better towards BS II for CO and HC emissions. The reason is the wider range of BS II (older) norm which let a higher number of cars pass through (Fig. 4.262).

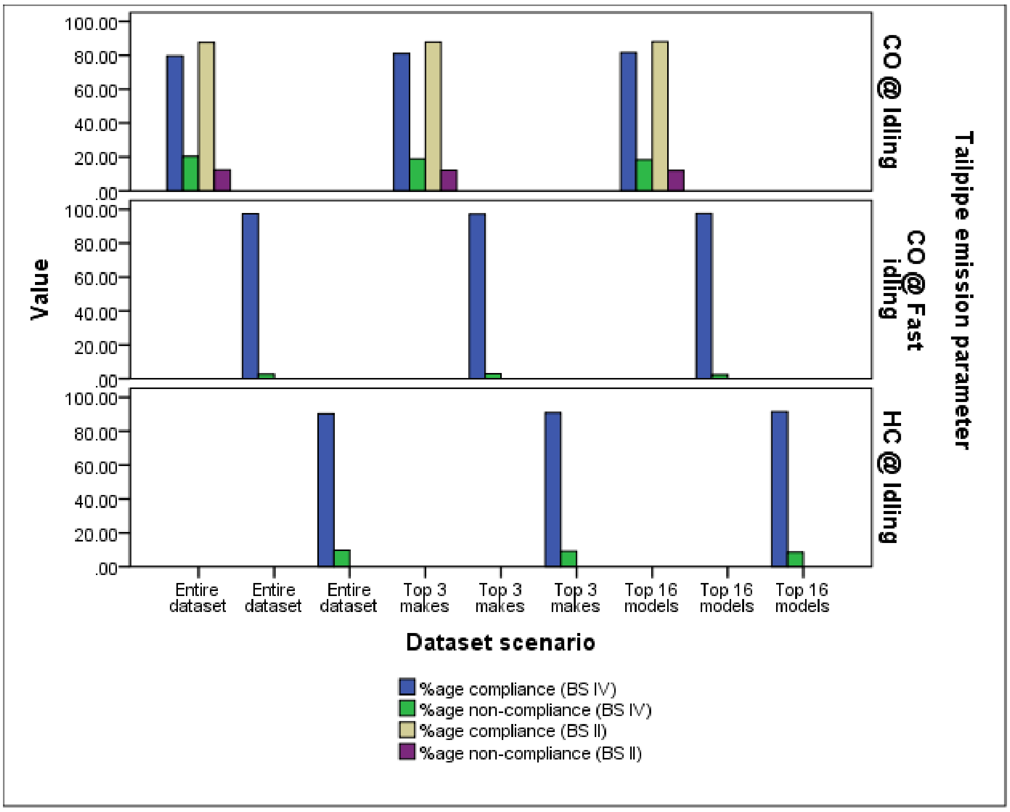


Fig. 4.262 Emission compliance levels for PDPCs (all datasets)

The emission compliance level was also analyzed for two vehicle-related aspects, such as, emission norm during manufacturing and vehicle maintenance. The boxplots depicting the scenario for emission norms used in the present study reveal that BS IV-compliant petrol-driven passenger cars emit the lowest range of CO in both idle and fast idle scenarios while in the case of HC emission the apparent high degree of outliers seen in emission norm parameter do not support this outcome. The effect of the maintenance category of vehicles has a more pronounced effect on CO and HC compliances with ‘very good’ and ‘good’ categories of vehicles always emitting within BS IV emission norm (Figs. 4.263 – 4.265).

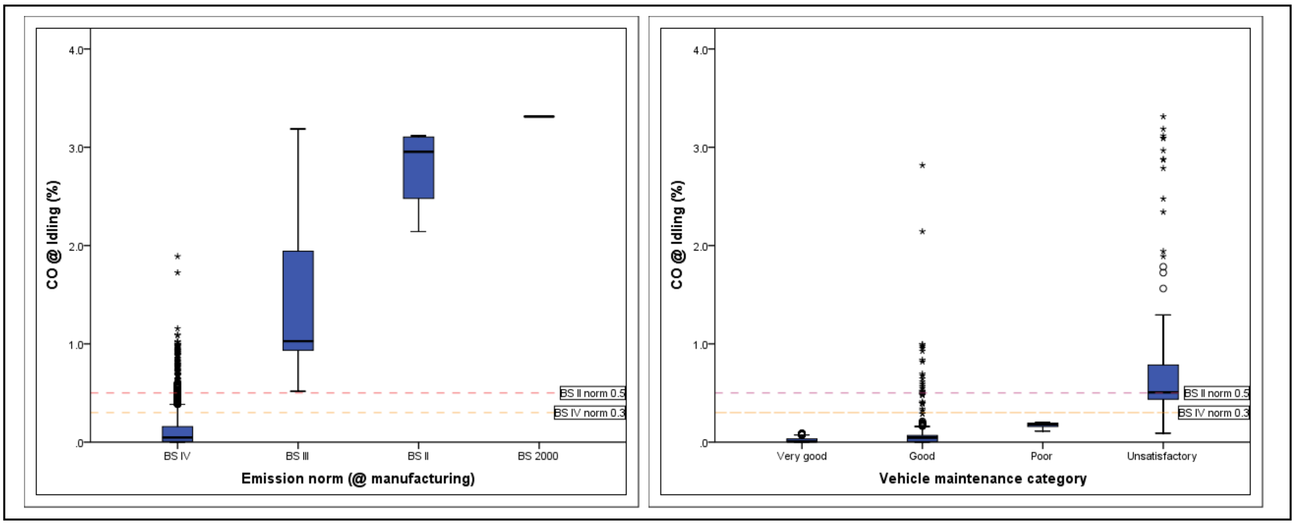


Fig. 4.263 Emission norm and maintenance category vs. CO emission (at idling)

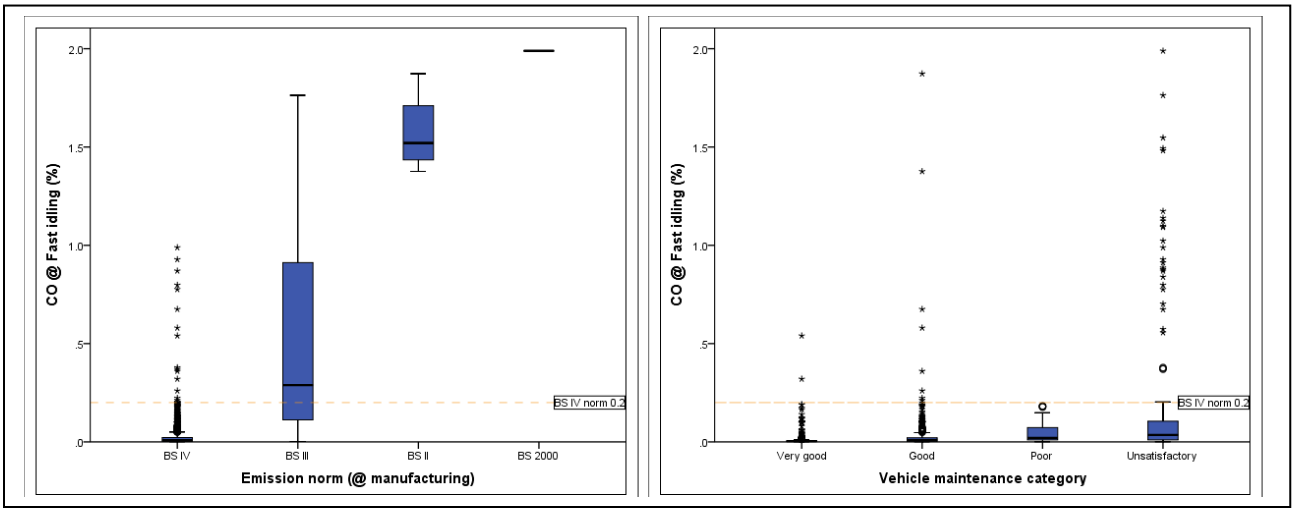


Fig. 4.264 Emission norm and maintenance category vs. CO emission (at fast idling)

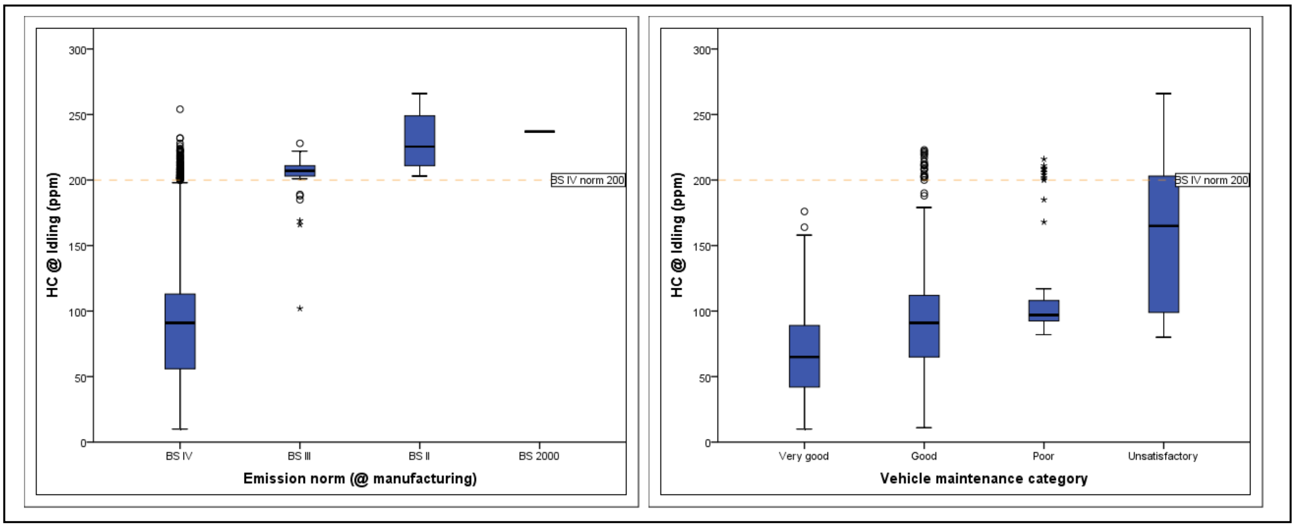


Fig. 4.265 Emission norm and maintenance category vs. HC emission (at idling)

Benefitting from the wider range of BS II norms compared to BS IV, even better compliance is seen as only 'unsatisfactory' category vehicles emit in violation of BS II standard except HC. Make-wise compliance scenario for petrol cars is presented in Fig. 4.266 which reveals that HCIL exhibits the highest emission compliance levels or all emission test parameters (i.e., CO @ idling, fast idling and HC @ idling for both BS IV and BS II norms) followed by HMIL and MSIL makes. The maximum degree of non-compliance to both emission norms for all the testing parameters was depicted by MSIL make.

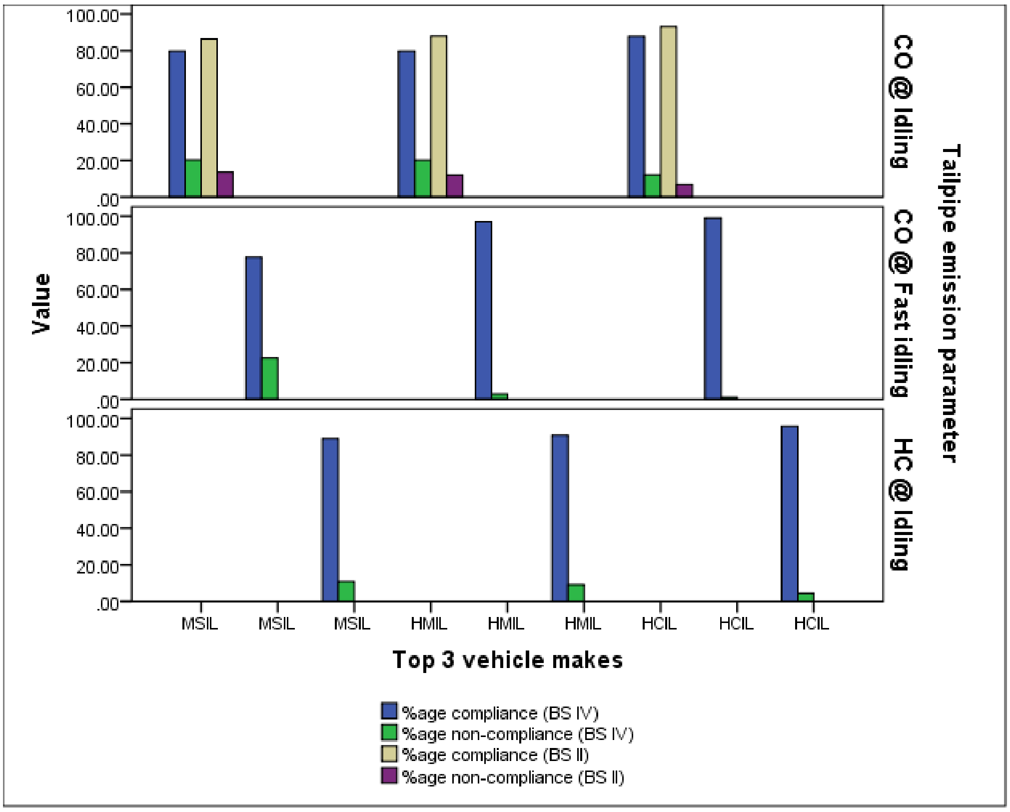


Fig. 4.266 Emission compliance levels for PDPCs (top 3 makes)

Model-wise compliance status finds Amaze, Baleno, Eeco, Grand i10 and Nexon to be the most compliant models for various test parameters achieving almost 100% compliance towards BS IV norms. Few more models get added to the best complying models in CO @ Fast idling conditions (Fig. 4.267). Although the observed high level of compliance is largely attributable to the improvement in engine designs in the recent decade, however, it is also due to the leniency of the applicable emission norms. The wider range of CO and HC concentrations both allows the vehicles to pass through the PUC certification and keep plying on the road despite the fact that it may be compliant just by a ppm or a decimal fraction of % concentration (in the case of HC and CO emissions) still emitting environmentally worse values in terms of mass emission. The leniency in PUC (in-use) certification norm are drawing criticism (Dandapat et al. 2020) and should be improved for stringency even in fast idling test modes.

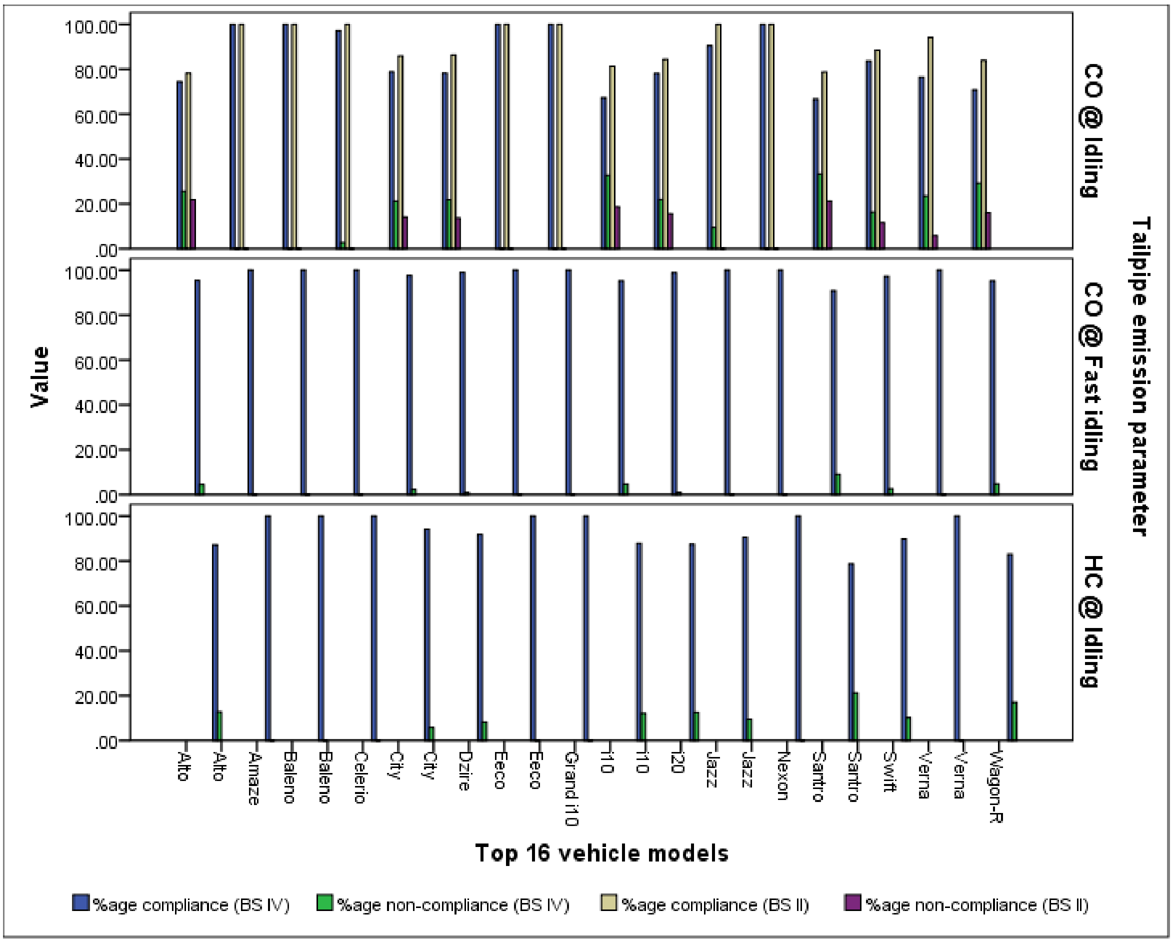


Fig. 4.267 Emission compliance levels for PDPCs (top 16 models)

The status of compliance of diesel cars for different dataset scenarios is presented in Fig. 4.268 followed by Fig. 4.270 and 4.271 depicting the same for the make and model-wise status respectively. It is again observed that all datasets reveal a very high level of compliance to both BS IV and BS III norms for SE (HSU) in FAST mode of testing. As the BS III benchmark is higher than that of BS IV (65 HSU against 50 HSU), compliance of diesel cars towards BS III is significantly and logically so, higher in all dataset conditions. Top 13 models' dataset scenario fares better compared to other datasets in terms of non-compliance to both BS III and BS IV norms returning the lowest values.

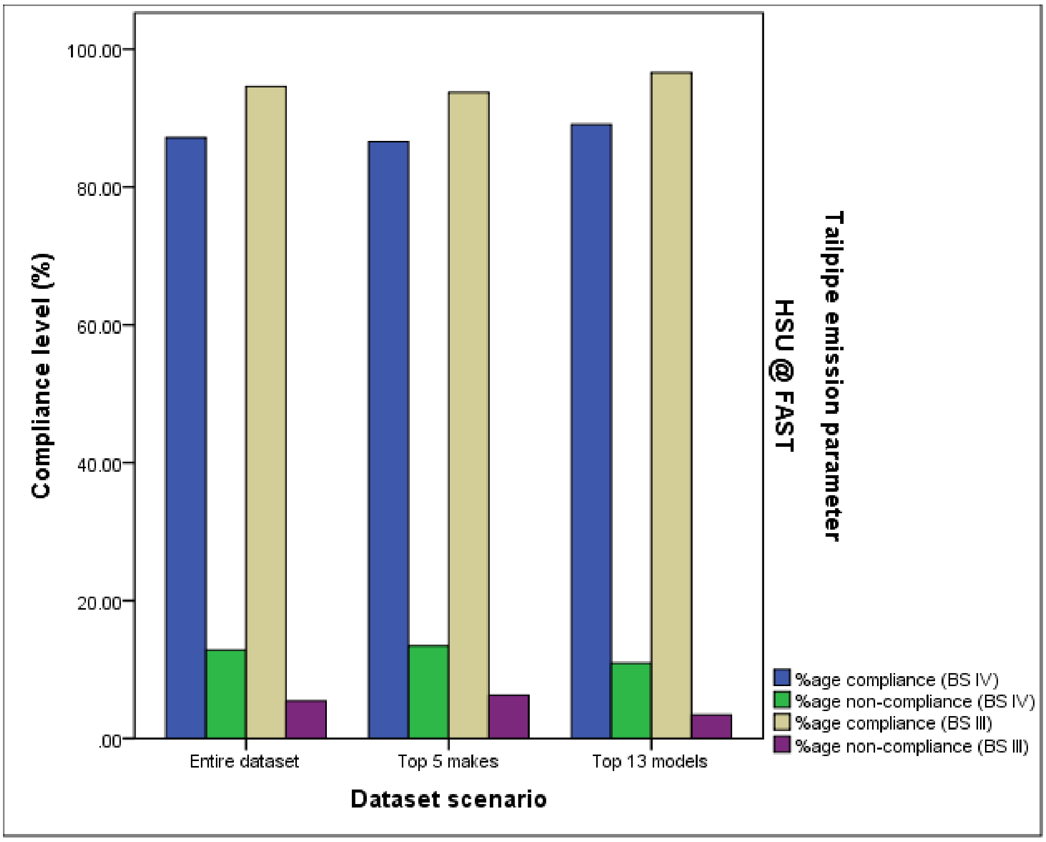


Fig. 4.268 Emission compliance levels for DDPCs (all datasets)

The emission compliance levels analyzed for emission norms during manufacturing and vehicle maintenance parameters in the case of diesel-driven passenger cars are presented in Fig. 4.269. The boxplots show that BS IV-compliant diesel cars emit the lowest range of HSU emission followed by BS II-compliant vehicles. Similar to petrol-driven cars, maintenance category of vehicles is observed to have more apparent effect on HSU emission and except ‘unsatisfactory’ category, all other vehicles possessing ‘very good’ and ‘good’ categories of vehicles always emit within BS IV emission norm. Even ‘poor’ category diesel cars were found to be compliant with BS IV norms although their compliance is just on the threshold.

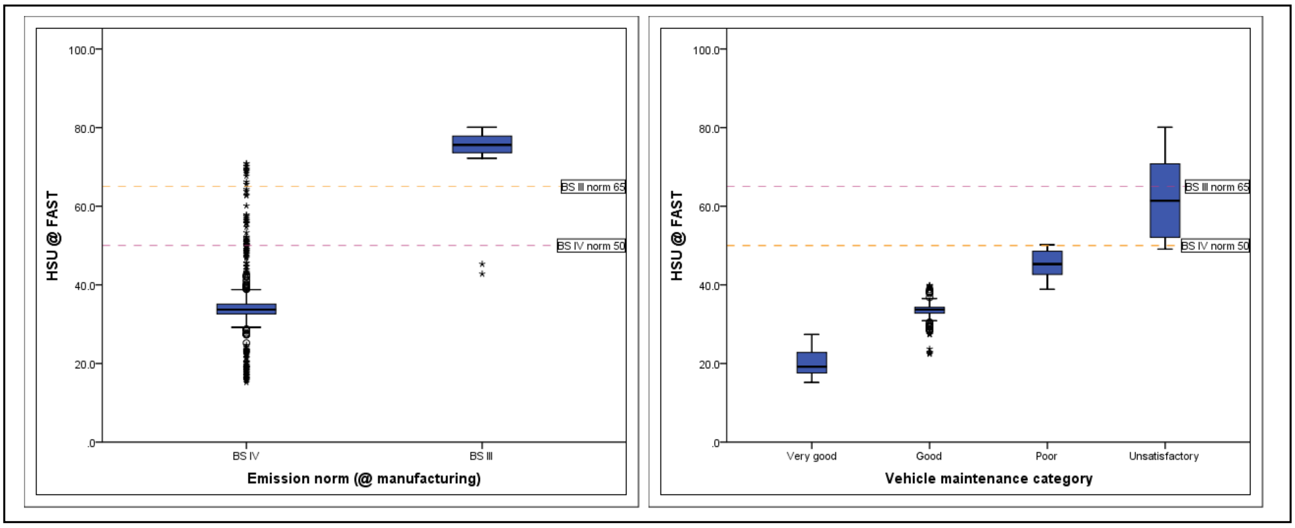


Fig. 4.269 Emission norm and maintenance category vs. SE (HSU @ FAST)

Make-wise, HMIL performs the best towards both the emission standards, followed by MSIL and TKMPL. MML and FIPL have higher percentage of non-compliance, especially for BS IV. Amaze, Verna, Duster, Brezza and Ciaz depict the highest degree of compliance for both BS IV and BS II emission norms of ES (HSU) showing almost 100% compliance. Figo leads the list of lowest levels of compliance followed by Scorpio, i20 and Swift models.

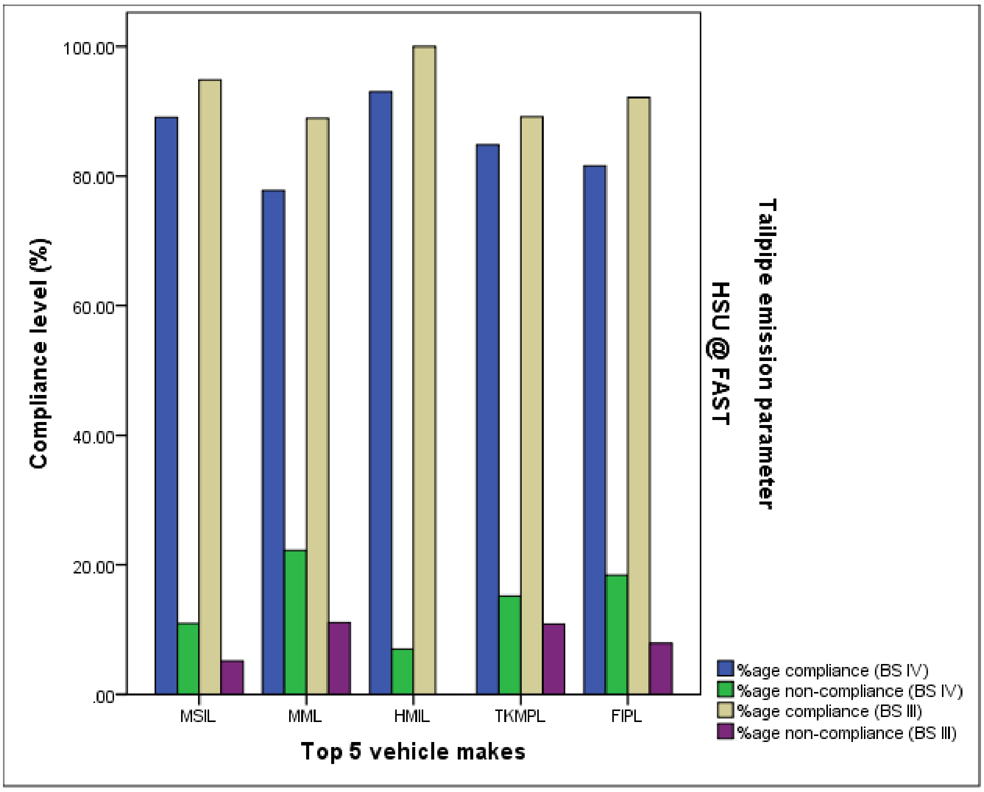


Fig. 4.270 Emission compliance levels for DDPCs (top 5 makes)

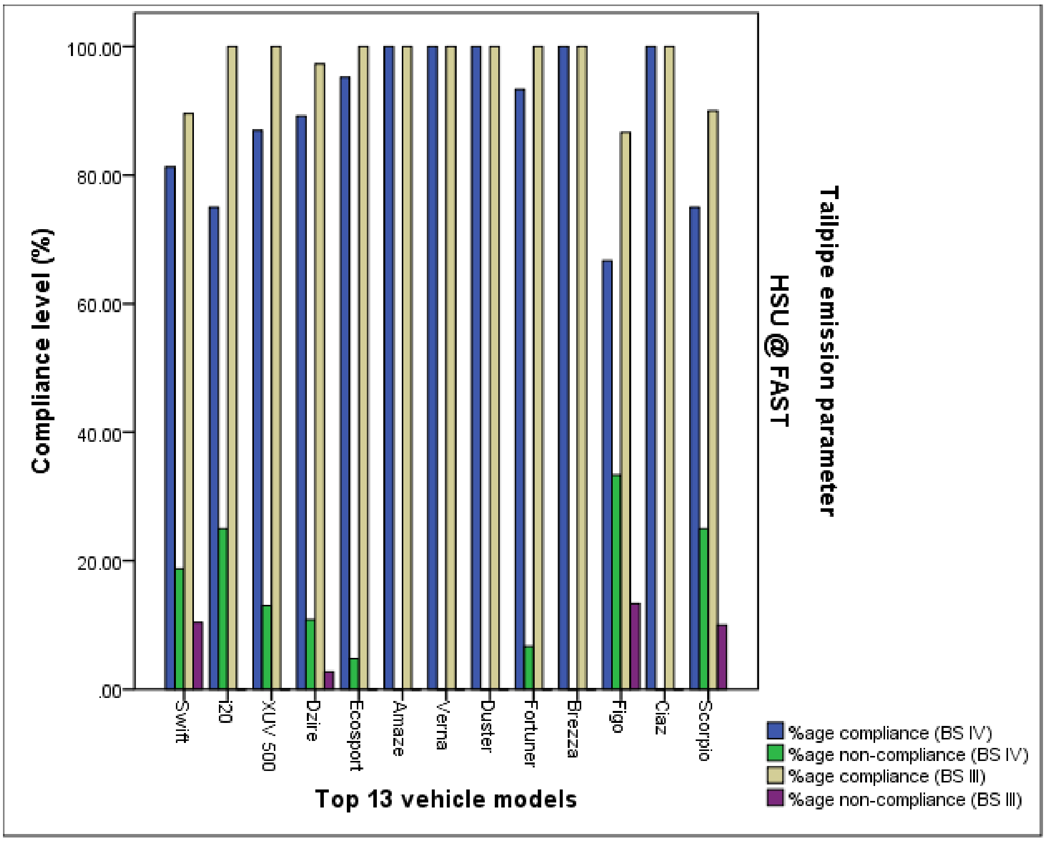


Fig. 4.271 Emission compliance levels for diesel-driven PCs (top 13 models)

4.3 Comparison of idle and fast idle CO and HC emissions vs. vehicle age and mileage

The tailpipe emission data collected during the emission testing program was also analyzed to assess the comparison of CO and HC emissions with respect to vehicle and mileage under both idle and fast idle testing conditions.

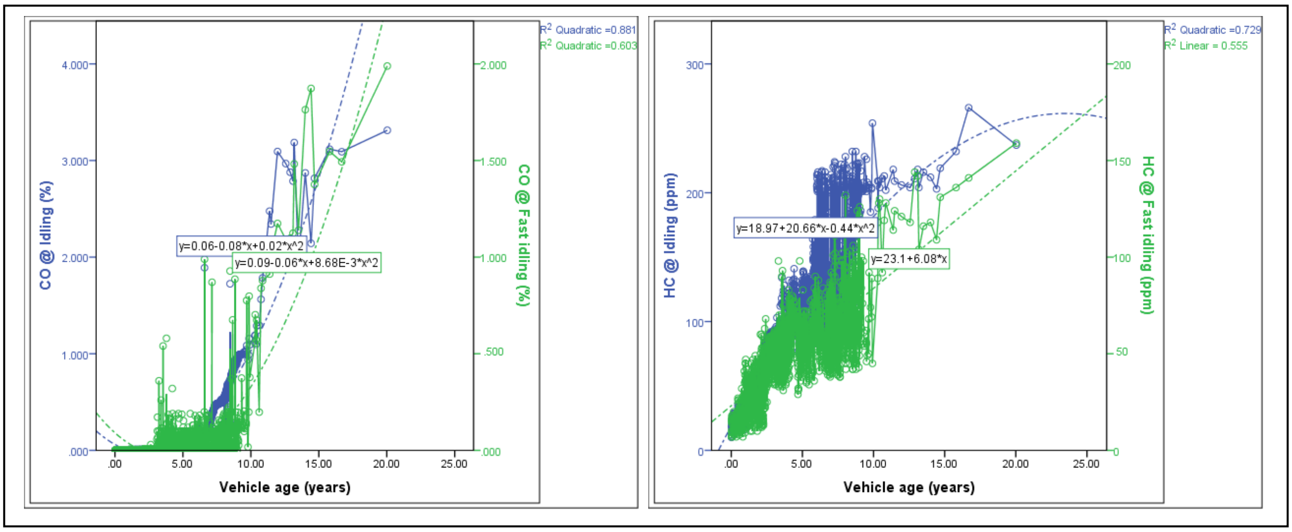


Fig. 4.272 CO and HC @ Idling and @ Fast idling vs. vehicle age for PDPCs

The relative standing of idle and fast idle test conditions is depicted in Fig. 4.272 for the variation of CO and HC emission with reference to vehicle age and in Fig. 4.273 for vehicle mileage. A glance at the trendlines relating to the two test conditions reveals that fast idle test condition yields lower values of CO and HC emissions than those for the idle test condition.

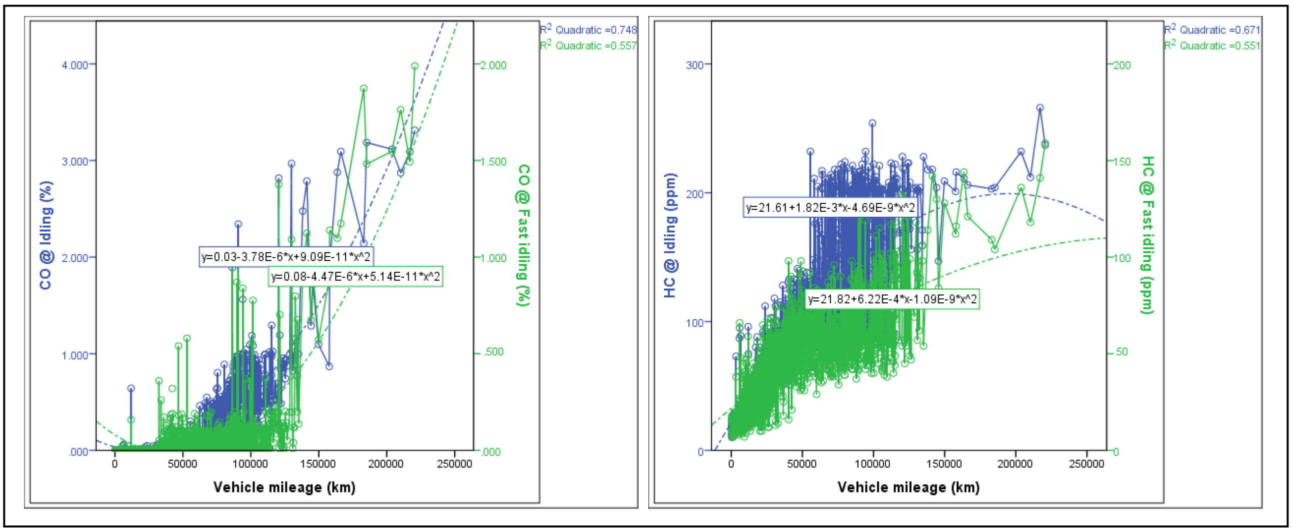


Fig. 4.273 CO and HC @ Idling and @ Fast idling vs. vehicle mileage for PDPCs

It, therefore, reflects that, if the fast-idle test condition is also permitted in the country and is linked with PUC certification process, the standardization procedure must look into the lowering of the values suitably than those prescribed for idle test conditions. For e.g., for the upcoming BS standard the CO @ Idling value of norm may be brought down from 0.3 % to 0.1 % and at the same time, the CO @ Fast idling value may further be tightened from the existing 0.2 % to 0.05 %. On similar lines, the standard values of HC may be suitably made more stringent (say 50 ppm from the existing 200 ppm at idling condition) with the introduction of HC @ Fast idling into PUC certification process which may be fixed at 25 ppm or so.

4.4 Construction of vehicular exhaust emission index (EEI)

The present study attempted to present a unique approach to formulating the exhaust emission index or EEI. In other words, applying the air quality indexing (AQI) principle to the tailpipe emission data was conducted. As AQI can point towards ambient air quality in terms of a range of numerical value, each presenting an associated effect, EEI was conceptualized so that depending upon numerical values constructed analyzing tailpipe emission data of cars, a scale can be presented stating the emission quality class or category of a vehicle. Application of exhaust emission indexing for such cars was undertaken in the present study as an important tool for assessing the emission status of vehicles. The development of EEI carries information about the intra-vehicle emission evaluation necessary for implementing effective I/M (Inspection/Maintenance) programs worldwide. It is recommended that this tool be adopted by several countries perplexed by severity of indigenous automobile pollution. This novel approach used CO and HC's volumetric concentration data from 1580 petrol-driven cars monitored in idling test conditions. The sample size represented passenger cars of different makes and models plying on the roads of NCT (National Capital Territory) of Delhi, India.

4.4.1 EEI conceptualization

As the EEI is conceptualized on the lines of AQI, two basic steps (generally used in construction of quality indexing) were used in the formulation of the EEI (Fig. 4.274).

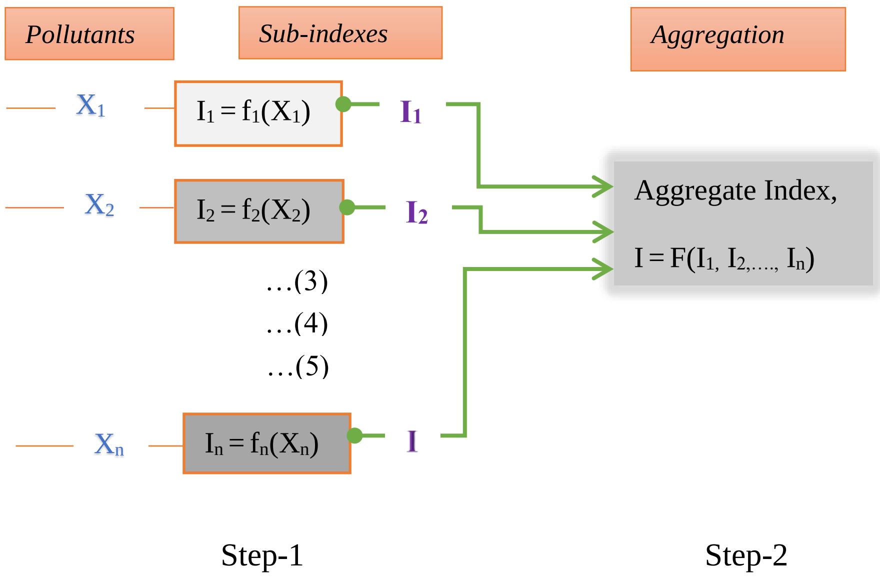


Fig. 4.274 Steps in formulation of EEI

where,

X_1 = CO @ idling test condition (in % terms)

X_2 = HC @ idling test condition (in ppm, parts per million terms)

I_1 = Sub-index for CO

I_2 = Sub-index for HC

In the first step, the sub-indexes for CO and HC were calculated followed by their aggregation into index (EEI).

4.3.1.1 Calculation of sub-indexes for CO and HC

Calculation of sub-index was affected using the following indexing formula widely used in the construction of indices by scientists and researchers working in the frontiers of air pollution and medical sciences.

$$Ip = \frac{I_{Hi} - I_{Lo}}{BP_{Hi} - BP_{Lo}} (Cp - BP_{Lo}) + I_{Lo} \qquad (1)$$

where,

Ip = the sub-index for CO or HC

Cp = the observed tailpipe concentration of CO or HC (in % or ppm terms)

BP_{Hi} = the concentration breakpoint ≥ to Cp

BP_{Lo} = the concentration breakpoint ≤ to Cp

I_{Hi} = the EEI value corresponding to BP_{Hi}

I_{Lo} = the EEI value corresponding to BP_{Lo}

Breakpoints for CO and HC were ascertained using the highest and lowest concentration ranges as measured in idle testing mode during the tailpipe emission testing program which catered to about 1580 petrol-driven passenger cars of different makes and models. Two different methods were used for scaling while calculating the breakpoints for CO and HC, i.e., linear scaling and scaling based on BS (Bharat Stage) emission norms (LSM and BSNSM respectively, Table 4.28). The reason behind using two different scaling methods for breakpoint ranges was to have a rationale on high and low points. While the BSNSM has a much wider range of concentration breakpoints, the LSM has a narrower range. For example, the breakpoint range for CO in case of LSM varies from 0.001 to 0.199 whereas the same in case of BSNSM spans between 0.001 and 0.3, thereby denoting higher degree of the ‘high BP’ value (considering ‘good’ EEI category). Similar is the case for all other categories of EEIs (Table 4.28). Further, for HC in the ‘good’ EEI category, the LSM has the range of 1 to 99 against 1 to 200 in case of the BSNSM.

The linear scaling method helped identifying vehicles with relatively higher emission range but were able to pass the PUC certification test in view of prescribed (higher) cut-off emission concentration.

Table 4.28 Scaling methods used in breakpoints' determination

CO - BP Low (BP_{LO})	CO - BP High (BP_{HI})	HC - BP Low (BP_{LO})	HC - BP High (BP_{HI})	Index R - Low (I_{LO})	Index R - High (I_{HI})	Category
Method 1: Linear scaling (LSM)						
0.001	0.199	1	99	1	10	Good
0.2	0.299	100	199	11	20	Satisfactory
0.3	1.999	200	399	21	30	Poor
2	3.5+	400	499+	31	40+	Phase-out
Method 2: Scaling based on BS norms (BSNSM)						
0.001	0.3	1	200	1	10	Good
0.301	0.5	201	750	11	20	Satisfactory
0.501	3	751	1500	21	30	Poor
3.001	4+	1501	1600+	31	40+	Phase-out

BP = Breakpoint; R = Range

While fixing the breakpoint ranges for CO and HC, the index (EEI) ranges for high and low values were also defined. These varied from the lowest value being '1' to the highest value as 40+ and had same range in either of the scaling methods (Table 4.29). Further, the numerical and corresponding qualitative description of the EEI categories was also chalked-out in order to understand the relative standing of all the petrol-driven cars in terms of their EEI values.

Table 4.29 Proposed EEI category description

EEI range		Category	Numeric category	Description
1	10	Good	1	Compliant, no action needed
11	20	Satisfactory	2	Near compliant / non-compliant, call for maintenance as it may help vehicle become compliant again / remain compliant
21	30	Poor	3	Non-compliant, go for overhauling
31	40+	Phase-out	4	Non-compliant, identify for phasing-out

4.3.1.2 Aggregation of CO and HC sub-indexes into EEI

Various methods of aggregation of sub-indexes into a single Index (e.g., AQI) have been suggested by researchers in the past, e.g., Linear sum aggregation form (LSAF) Weighed additive form (WAF), Root sum power form (RSPF), Root mean square form (RMSF) and Maximum operator form (MOF) are the ones extensively reported in the literature.

Ott (1978) indicated that, primarily, the subindices were expressed as linear functions of the ratio of pollutant concentration ‘q’ to a standard concentration ‘q_s’, i.e.,

$$S = Ss\,(q/qs) \tag{2}$$

where S = subindex and Ss = a scaling coefficient that is 500 in Indian National Ambient Air Quality Index (NAAQS) and 1 in the Russian air pollution monitoring studies. The standard concentration q_s = significant harm level value of q in NAAQS and the maximum permissible concentration in the Russian air pollution monitoring studies. The sub-indexes are aggregated to yield an overall air pollution index. The linear sum aggregation (LSAF) is described by –

$$I = \sum_{i=1}^{N} Si \tag{3}$$

where I = aggregate index; N = the number of subindices; and Si = i^{th} subindex.

Root mean square aggregation form (RMSF) is also used for aggregation –

$$I = \left(\sum_{i=1}^{N} S^2 i \right)^{0.5} \tag{4}$$

Literature finds application of maximum operator as an aggregation function (MOF) –

$$I = \text{Max. } (I_1, I_2, 1_3, \ldots\ldots\ldots, I_n) \tag{5}$$

Weighed additive form (WAF) is also used to aggregate the sub-indexes using weightage assigned to each sub-index –

$$I = \sum_{i=1}^{N} w_i I_i \tag{6}$$

Where w = weightage assigned to each sub-index

Sharma and Tyagi (2000) proposed a refined Root sum power form (RSPF) of aggregation –

$$I=\left(\sum_{i=1}^{N} Si^{p}\right)^{1/p} \tag{7}$$

Where p = positive real number > 1.

In the present study, four methods of aggregation were used to construct and compare the resultant EEIs – Weighed additive form (WAF), Root sum power form (RSPF), Root mean square form (RMSF) and Maximum operator form (MOF). The application of WAF required assigning modest weightages to CO and HC based on some reliable aspects reported in past research. However, the literature reported shortcomings in relation to various methods of construction of existing AQIS. For e.g., existing API (Air pollution index) in Hong Kong did not consider the combined effects of all pollutants on human health and was replaced with a new API (called Revised API or RAPI) as it was based on a more comprehensive method combining all pollutants (Lu et al., 2011). Sicard et al. (2011) used an aggregated risk index (ARI) based on the exposure-response relationship and Relative Risk (RR). The resulting index was defined to reflect the contribution of individual pollutants to total risk which could be related to short term effect or mortality.

Gorai et al. (2015) used the principle of the Fuzzy theory and matrixes to reach a single-digit index. The approach of this AQI was to generate an index to determine the actual health risk at a particular location. To achieve this, it took into consideration both pollutant parameter (PI) as well as exposure parameter (EI). These two matrixes were used to establish a third matrix called FAQHI (fuzzy air quality health index) to calculate the final index. Another unique index was conceived as City Noise-Air in the sense that it incorporated the effect of noise pollution in the AQI. The index was divided into two factors having equal weightage representing air and noise. City noise index had two values i.e., 0 (when the noise limit is exceeded and 1 (in case of reverse scenario). City air index was calculated using WAF and then was combined with City noise to get into final index. This concept used a 0.2 weightage factor for all the pollutants considered in defining the Air index (Silva and Mendes, 2012).

Thach et al. (2018) reported a predictive air quality index focusing on predicting their impact on health. Considering only four pollutants of interest (SO_2 NO_2, O_3 and PM_{10}), the calculation was divided into 2 parts with the first step being the calculation of sub-indexing and the second being aggregating the sub-indexes to form an overall index. They used equations 2 and 7 to calculate and present Hong Kong Air Quality Index (HKAQI).

Sowlat et al. (2011) proposed a Fuzzy AQI (FAQI) based on a linguistic, if/then principal instead of a complex equation, with the help of 72 rules. For example, Rule 10 states that If PM_{10} is “high” then FAQI is “unhealthy”. This type of linguistic definition made it easier to incorporate expert opinion in a more unanimous way. Another important aspect of the proposed FAQI is that it assigned weightage to each pollutant basis their currently known impact on human health. The pollutants were divided into two groups namely ‘criteria’ (consisting of CO, O_3, PM_{10}, SO_2, and NO_2) and ‘BTEX’ (consisting of HCs, such as benzene, toluene, ethyl benzene, xylene, and 1,3-butadiene) The weightage factors of 0.7 and 0.3 were assigned to criteria and BTEX groups, respectively.

After a thorough literature survey and recent trends on the development or refinement of AQI, it was found that fixing weightage based on the human health aspects of CO and HC was the most reliable method of. Therefore, a weightage factor of 0.41 was assigned to CO while HC being assigned a weightage factor of 0.59. These two factors were derived from the weightages proposed in the FAQI study by Sowlat et al. (2011) by scaling the fractions of CO and HC in ‘criteria’ and ‘BTEX’ group. Besides, the weightage factor of 0.7 and 0.3 for CO and HC was also used to see any difference in the resultant EEI and its categories, if any.

Following steps 1 and 2 and in view of the literature survey, the EEI values and categories were calculated for the whole dataset (i.e., 1580 petrol-driven passenger cars) using four different aggregation methods. A snapshot of the EEI calculations, resultant EEI categories considering 15 (fifteen) vehicles based on different breakpoint scaling methods is presented in the subsequent parts (Tables 4.30 – 4.34).

Table 4.30 Sub-index calculations using Linear scaling method, LSM (15 sample cars)

Vehicle regn. No.	**CO @ Idling (%)**	**HC @ Idling (ppm)**	**BP value below CO (BPLo)**	**BP value above CO (BPHi)**	**Index value - Low (ILO)**	**Index value - High (IHi)**	***Sub-index for CO (Ip)***	**BP value below HC (BPLo)**	**BP value above HC (BPHi)**	**Index value - Low (ILO)**	**Index value - High (IHi)**	***Sub-index for HC (Ip)***
DL9CU3526	0.242	96	0.2	0.299	11	20	***14.82***	1	99	1	10	***9.72***
DL9CAB7885	0.266	207	0.2	0.299	11	20	***17.00***	200	399	21	30	***21.32***
DL8CNA7723	0.289	114	0.2	0.299	11	20	***19.09***	100	199	11	20	***12.27***
DL1CM7288	0.284	99	0.2	0.299	11	20	***18.64***	1	99	1	10	***10.00***
DL9CAG1519	0.299	202	0.2	0.299	11	20	***20.00***	200	399	21	30	***21.09***
DL12CL3925	0.007	49	0.001	0.199	1	10	***1.27***	1	99	1	10	***5.41***
DL10CB4244	0.289	214	0.2	0.299	11	20	***19.09***	200	399	21	30	***21.63***
DL2CAP0818	0.296	95	0.2	0.299	11	20	***19.73***	1	99	1	10	***9.63***
DL10CB4282	0.302	127	0.3	1.999	21	30	***21.01***	100	199	11	20	***13.45***
DL9CAQ7195	0.007	46	0.001	0.199	1	10	***1.27***	1	99	1	10	***5.13***
DL2CAZ5591	0.007	31	0.001	0.199	1	10	***1.27***	1	99	1	10	***3.76***
DL2CAW0881	0.008	86	0.001	0.199	1	10	***1.32***	1	99	1	10	***8.81***
DL4CAX7946	0.006	54	0.001	0.199	1	10	***1.23***	1	99	1	10	***5.87***
DL4CAQ4093	0.305	92	0.3	1.999	21	30	***21.03***	1	99	1	10	***9.36***
DL10CB4085	0.316	201	0.3	1.999	21	30	***21.08***	200	399	21	30	***21.05***

Table 4.31 Sub-index calculations using BS norm scaling method, BSNSM (15 sample cars)

Vehicle regn. No.	**CO @ Idling (%)**	**HC @ Idling (ppm)**	**BP value below CO (BPLo)**	**BP value above CO (BPHi)**	**Index value - Low (ILO)**	**Index value - High (IHi)**	***Sub-index for CO (Ip)***	**BP value below HC (BPLo)**	**BP value above HC (BPHi)**	**Index value - Low (ILO)**	**Index value - High (IHi)**	***Sub-index for HC (Ip)***
DL9CU3526	0.242	96	0.001	0.3	1	10	***8.25***	1	200	1	10	***5.30***
DL9CAB7885	0.266	207	0.001	0.3	1	10	***8.98***	201	750	11	20	***11.10***
DL8CNA7723	0.289	114	0.001	0.3	1	10	***9.67***	1	200	1	10	***6.11***
DL1CM7288	0.284	99	0.001	0.3	1	10	***9.52***	1	200	1	10	***5.43***
DL9CAG1519	0.299	202	0.001	0.3	1	10	***9.97***	201	750	11	20	***11.02***
DL12CL3925	0.007	49	0.001	0.3	1	10	***1.18***	1	200	1	10	***3.17***
DL10CB4244	0.289	214	0.001	0.3	1	10	***9.67***	201	750	11	20	***11.21***
DL2CAP0818	0.296	95	0.001	0.3	1	10	***9.88***	1	200	1	10	***5.25***
DL10CB4282	0.302	127	0.301	0.5	11	20	***11.05***	1	200	1	10	***6.70***
DL9CAQ7195	0.007	46	0.001	0.3	1	10	***1.18***	1	200	1	10	***3.04***
DL2CAZ5591	0.007	31	0.001	0.3	1	10	***1.18***	1	200	1	10	***2.36***
DL2CAW0881	0.008	86	0.001	0.3	1	10	***1.21***	1	200	1	10	***4.84***
DL4CAX7946	0.006	54	0.001	0.3	1	10	***1.15***	1	200	1	10	***3.40***
DL4CAQ4093	0.305	92	0.301	0.5	11	20	***11.18***	1	200	1	10	***5.12***
DL10CB4085	0.316	201	0.301	0.5	11	20	***11.68***	201	750	11	20	***11.00***

Table 4.32 EEI calculation using Linear scaling method, LSM (15 sample cars)

S. No.	Vehicle regn. No.	Sub-index for CO (Ip)	Sub-index for HC (Ip)	Max. operator (MOF)	Weighed additive form (WAF - using CO = 0.7, HC = 0.3)	Weighed additive form (WAF - using CO = 0.41, HC = 0.59)	Root sum power form (RSPF)	Root mean square form (RMSF)
1	DL9CU3526	14.82	9.72	14.82	13.29	11.81	16.10	12.53
2	DL9CAB7885	17.00	21.32	21.32	18.29	19.55	24.44	19.28
3	DL8CNA7723	19.09	12.27	19.09	17.05	15.07	20.65	16.05
4	DL1CM7288	18.64	10.00	18.64	16.05	13.54	19.55	14.96
5	DL9CAG1519	20.00	21.09	21.09	20.33	20.64	25.90	20.55
6	DL12CL3925	1.27	5.41	5.41	2.51	3.71	5.43	3.93
7	DL10CB4244	19.09	21.63	21.63	19.85	20.59	25.75	20.40
8	DL2CAP0818	19.73	9.63	19.73	16.70	13.77	20.46	15.52
9	DL10CB4282	21.01	13.45	21.01	18.74	16.55	22.71	17.64
10	DL9CAQ7195	1.27	5.13	5.13	2.43	3.55	5.16	3.74
11	DL2CAZ5591	1.27	3.76	3.76	2.02	2.74	3.80	2.80
12	DL2CAW0881	1.32	8.81	8.81	3.56	5.74	8.82	6.30
13	DL4CAX7946	1.23	5.87	5.87	2.62	3.96	5.89	4.24
14	DL4CAQ4093	21.03	9.36	21.03	17.53	14.14	21.63	16.27
15	DL10CB4085	21.08	21.05	21.08	21.07	21.06	26.54	21.07

Table 4.33 EEI calculation using BS norm scaling method, BSNSM (15 sample cars)

S. No.	Vehicle regn. No.	Sub-index for CO (Ip)	Sub-index for HC (Ip)	Max. operator (MOF)	Weighed additive form (WAF - using CO = 0.7, HC = 0.3)	Weighed additive form (WAF - using CO = 0.41, HC = 0.59)	Root sum power form (RSPF)	Root mean square form (RMSF)
1	DL9CU3526	8.25	5.30	8.25	7.37	6.51	8.93	6.93
2	DL9CAB7885	8.98	11.10	11.10	9.61	10.23	12.79	10.09
3	DL8CNA7723	9.67	6.11	9.67	8.60	7.57	10.42	8.09
4	DL1CM7288	9.52	5.43	9.52	8.29	7.11	10.07	7.75
5	DL9CAG1519	9.97	11.02	11.02	10.28	10.59	13.25	10.51
6	DL12CL3925	1.18	3.17	3.17	1.78	2.35	3.22	2.39
7	DL10CB4244	9.67	11.21	11.21	10.13	10.58	13.23	10.47
8	DL2CAP0818	9.88	5.25	9.88	8.49	7.15	10.35	7.91
9	DL10CB4282	11.05	6.70	11.05	9.74	8.48	11.81	9.13
10	DL9CAQ7195	1.18	3.04	3.04	1.74	2.27	3.09	2.30
11	DL2CAZ5591	1.18	2.36	2.36	1.53	1.87	2.45	1.86
12	DL2CAW0881	1.21	4.84	4.84	2.30	3.35	4.87	3.53
13	DL4CAX7946	1.15	3.40	3.40	1.82	2.48	3.44	2.54
14	DL4CAQ4093	11.18	5.12	11.18	9.36	7.60	11.53	8.69
15	DL10CB4085	11.68	11.00	11.68	11.47	11.28	14.30	11.34

Table 4.34 EEI categories using different scaling method (15 sample cars)

Vehicle regn. No.	EEI categories using linear scale method (LSM)					EEI categories using BS norm scale method (BSNSM)				
	Max. operator (MOF)	**Weighed additive form (WAF - using CO = 0.7, HC = 0.3)**	**Weighed additive form (WAF - using CO = 0.41, HC = 0.59)**	**Root sum power form (RSPF)**	**Root mean square form (RMSF)**	**Max. operator (MOF)**	**Weighed additive form (WAF - using CO = 0.7, HC = 0.3)**	**Weighed additive form (WAF - using CO = 0.41, HC = 0.59)**	**Root sum power form (RSPF)**	**Root mean square form (RMSF)**
DL9C U3526	Satisfactory	Satisfactory	Satisfactory	Satisfactory	Satisfactory	Good	Good	Good	Good	Good
DL9C AB7885	Poor	Satisfactory	Satisfactory	Poor	Satisfactory	Satisfactory	Good	Satisfactory	Satisfactory	Satisfactory
DL8C NA7723	Satisfactory	Satisfactory	Satisfactory	Poor	Satisfactory	Good	Good	Good	Satisfactory	Good
DL1C M7288	Satisfactory	Satisfactory	Satisfactory	Satisfactory	Satisfactory	Good	Good	Good	Satisfactory	Good
DL9C AG1519	Poor	Poor	Poor	Poor	Poor	Satisfactory	Satisfactory	Satisfactory	Satisfactory	Satisfactory
DL12C L3925	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
DL10C B4244	Poor	Satisfactory	Poor	Poor	Poor	Satisfactory	Satisfactory	Satisfactory	Satisfactory	Satisfactory
DL2C AP0818	Satisfactory	Satisfactory	Satisfactory	Poor	Satisfactory	Good	Good	Good	Satisfactory	Good
DL10C B4282	Poor	Satisfactory	Satisfactory	Poor	Satisfactory	Satisfactory	Good	Good	Satisfactory	Good
DL9C AQ7195	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
DL2C AZ5591	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
DL2C AW0881	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
DL4C AX7946	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
DL4C AQ4093	Poor	Satisfactory	Satisfactory	Poor	Satisfactory	Satisfactory	Good	Good	Satisfactory	Good
DL10C B4085	Poor	Poor	Poor	Poor	Poor	Satisfactory	Satisfactory	Satisfactory	Satisfactory	Satisfactory

The statistical difference in the resultant EEI values using the two different scaling methods was also plotted to ascertain the degree of variation (Fig. 4.275).

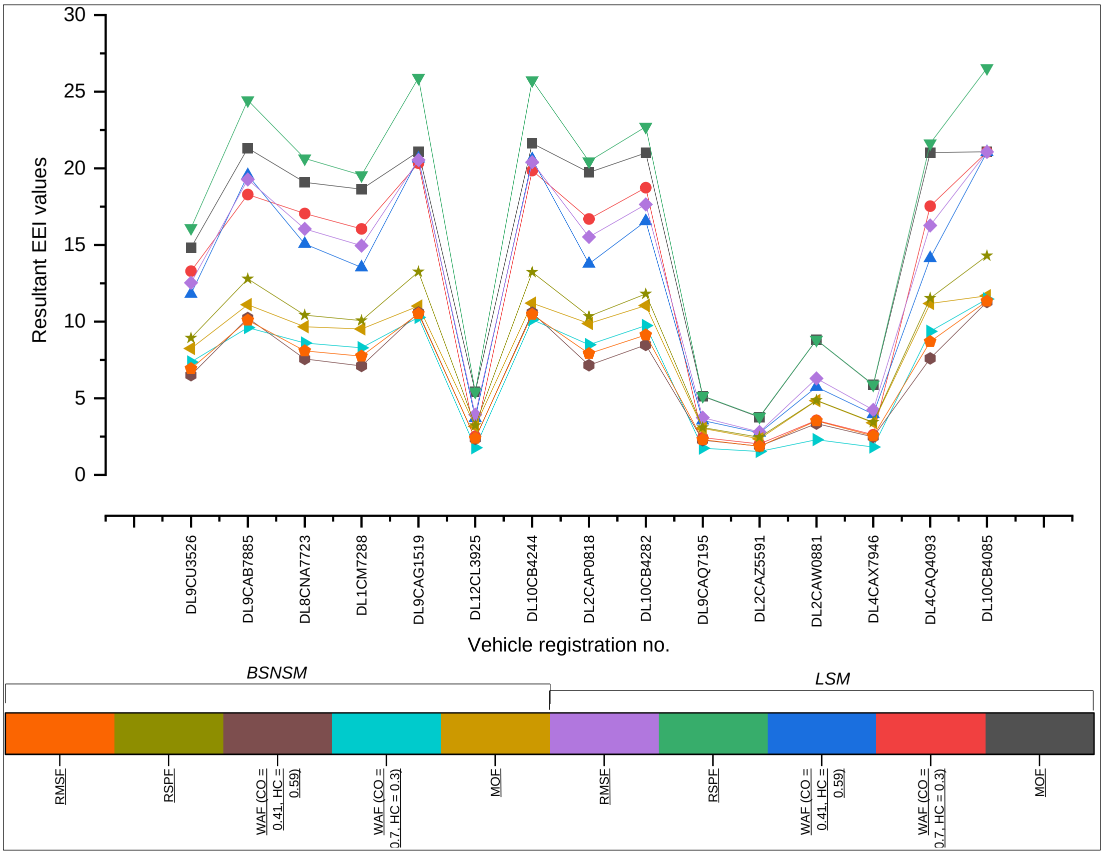


Fig. 4.275 EEI variations in respect of breakpoint scaling methods

It is revealed that the linear and BS scales yield significantly different EEI values and resultant vehicle classes. The former also picks up a better representation of how vehicles are performing in a narrow resolution of tailpipe exhaust emission values under idling conditions. The change in weightage values of CO and HC affects the EEI values (different EEIs are found for different weightages / weightage factors assigned to CO and HC each), but not the EEI class as such. Maximum operator (MOF) method of aggregation of sub-indexes into EEI yields the most reliable EEI values and resultant class(es) / categories with Root sum power form (RSPF) method following closely. It is further observed that the MOF and RSPF methods of aggregation are more reliable ones compared to the remaining options, as these are able to identify more ‘poor’ and ‘phase-out’ class(es) of EEI categories (Table 4.35).

Table 4.35 Number of vehicles in terms of EEI class (whole dataset, n = 1580)

EEI class	**Max. operator (MOF)**		**Weighed additive form (WAF - using CO = 0.7, HC = 0.3)**		**Weighed additive form (WAF - using CO = 0.41, HC = 0.59)**		**Root sum power form (RSPF)**		**Root mean square form (RMSF)**	
	Linear scale method									
	No. of vehicles	% of total	No. of vehicles	% of total	No. of vehicles	% of total	No. of vehicles	% of total	No. of vehicles	% of total
Good	945	59.81	1190	75.32	1141	72.22	868	54.94	1102	69.75
Satisfactory	277	17.53	192	12.15	289	18.29	349	22.09	305	19.30
Poor	345	21.84	187	11.84	150	9.49	343	21.71	167	10.57
Phase-out	13	0.82	11	0.70	0	0.00	20	1.27	6	0.38
	BS norm scale method									
Good	1223	77.41	1258	79.62	1271	80.44	1214	76.84	1257	79.56
Satisfactory	162	10.25	302	19.11	307	19.43	155	9.81	308	19.49
Poor	190	12.03	20	1.27	2	0.13	203	12.85	15	0.95
Phase-out	5	0.32	0	0.00	0	0.00	8	0.51	0	0.00

The Bland-Altman plot for each aggregation method considering both the scaling procedures were also drawn to check for agreement amongst the EEIs yielded by each method. The plot depicts itself like a scatterplot having the difference between the two measurements (Y-axis) against the average of the two measurements (X-axis). Thus, it provides a graphical display of bias (mean difference between the two techniques) with 95% limits of agreement.

The formula is given below:

$$\text{LoA} = \mu\text{m} \pm 1.96 * \sigma \qquad (8)$$

Where, LoA = limits of agreement; μm = mean observed difference, and σ = standard deviation of observed differences.

The resultant EEI ranges were also plotted representing error bars across all aggregation methods for both the scaling methods. The bars displayed the resultant EEIs at 95 % confidence interval and the mean in the boxes and interpolation values outside (Fig. 4.276 – 4.278).

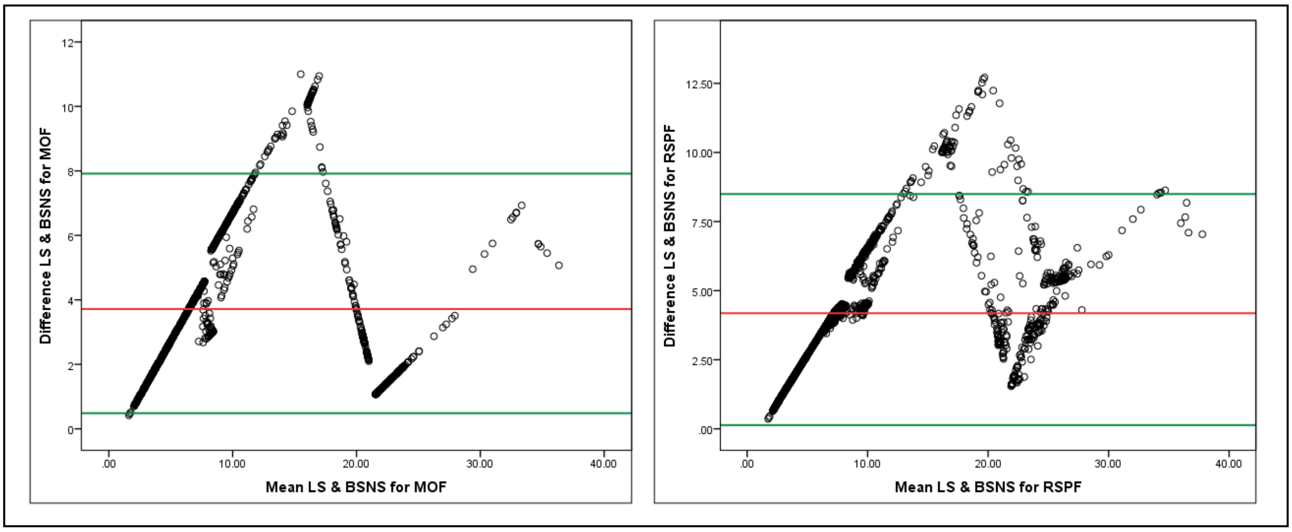


Fig. 4.276 Bland-Altman plot for MOF and RSPF aggregation methods for petrol-driven cars

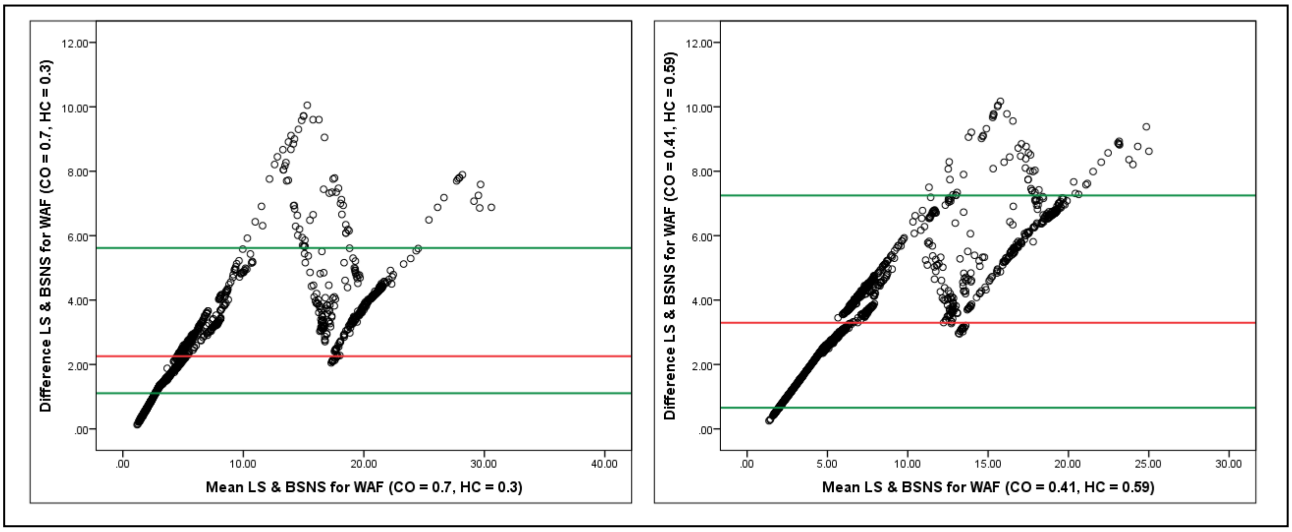


Fig. 4.277 Bland-Altman plot for WAF aggregation methods for petrol-driven cars

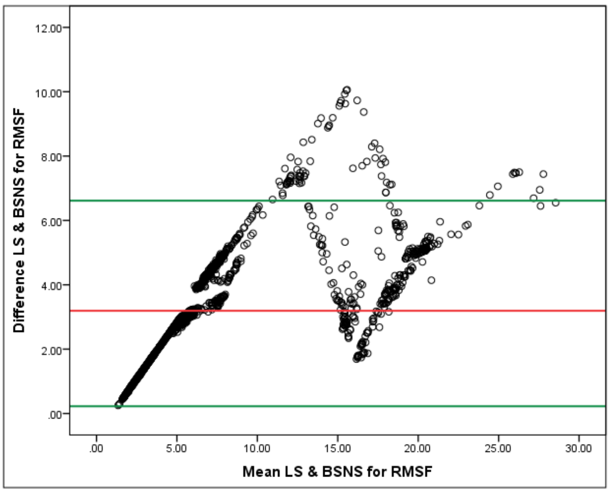
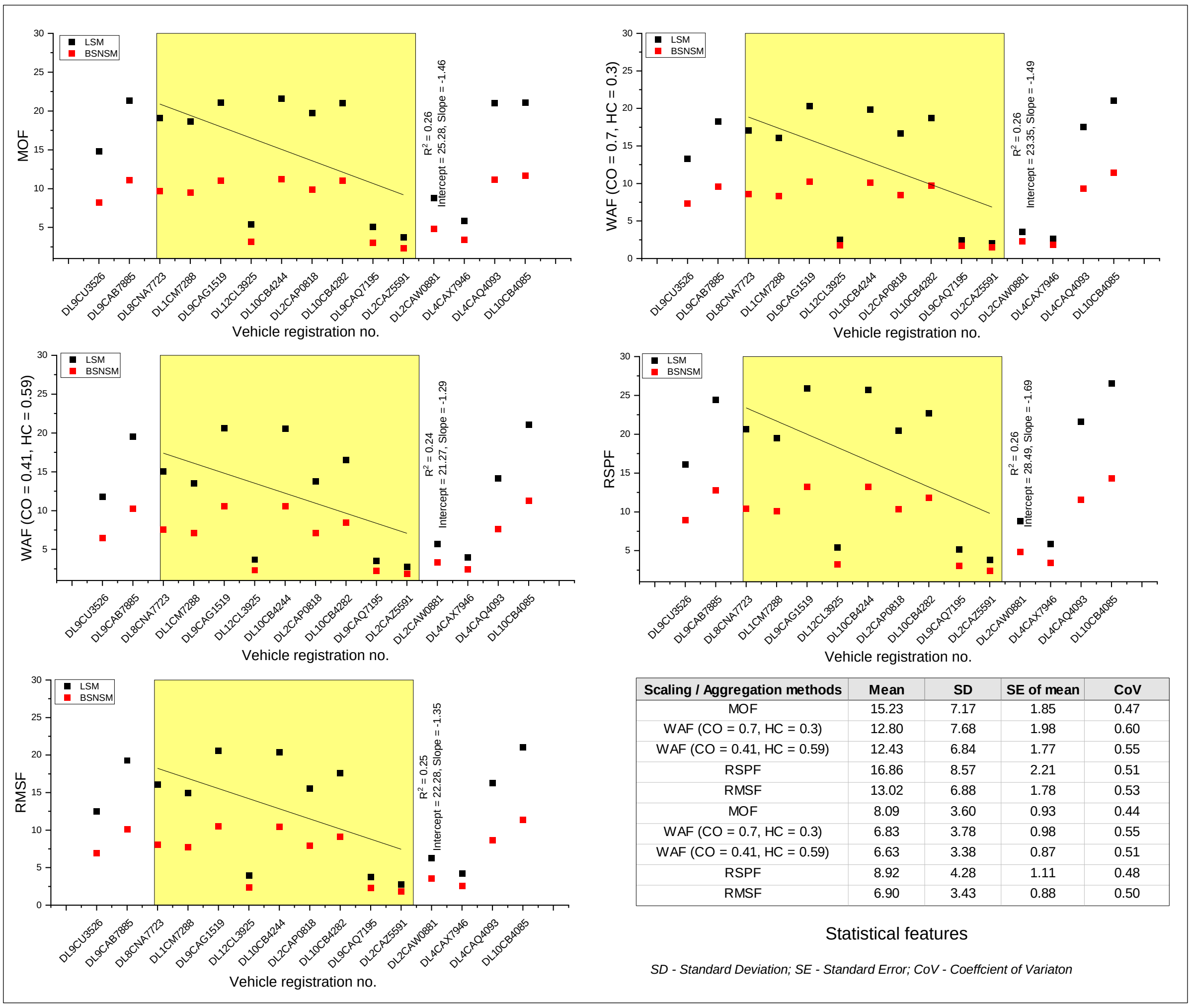


Fig. 4.278 Bland-Altman plot for RMSF aggregation method for petrol-driven cars



Scaling / Aggregation methods	Mean	SD	SE of mean	CoV
MOF	15.23	7.17	1.85	0.47
WAF (CO = 0.7, HC = 0.3)	12.80	7.68	1.98	0.60
WAF (CO = 0.41, HC = 0.59)	12.43	6.84	1.77	0.55
RSPF	16.86	8.57	2.21	0.51
RMSF	13.02	6.88	1.78	0.53
MOF	8.09	3.60	0.93	0.44
WAF (CO = 0.7, HC = 0.3)	6.83	3.78	0.98	0.55
WAF (CO = 0.41, HC = 0.59)	6.63	3.38	0.87	0.51
RSPF	8.92	4.28	1.11	0.48
RMSF	6.90	3.43	0.88	0.50

Statistical features

SD - Standard Deviation; SE - Standard Error; CoV - Coeffcient of Variaton

4.279 EEI range comparison across all aggregation methods

As can be seen from the plots, the MOF and RSPF methods look very similar to each other depicting close mean differences, lower and upper agreement limits compared to other two methods (Figs. 4.276 and 4.279). In WAF method, the change of weightage coefficients of CO and HC creates a lot of difference in agreement plot. Choosing the CO and HC weightages as 0.41 and 0.59 in the second scenario presents a better agreement (Figs. 4.277 and 4.279). RMSF method seems to have closely followed the agreement depicted by MOF and RSPF methods. After a careful consideration of the entire scenario of the resultant EEI values and categories, it is recommended to use Maximum operator form (MOF) method for aggregation of indexing (EEI formation) based on the fact that it is free from eclipses and overlapping while presenting reliable outcomes on vehicles' compliance levels in narrower ranges of emission values.

CHAPTER 5

CONCLUSION AND FUTURE PROSPECTS

The effect of the various vehicle and engine-related aspects on CO, HC, CO_2, O_2 and smoke (HS units) emissions along with λ and AFR parameters of the petrol and diesel-driven passenger cars of various makes and models plying in NCT of Delhi, India has been systematically analyzed. A novel concept of the Exhaust Emission Index (EEI) for petrol-driven passenger cars has also been formulated, considering the emission data collected during the present study. Based upon the analysis of data, results and discussion, the following inferences and recommendations are drawn:

1. It is revealed that the emission characteristics of petrol-driven passenger cars of various makes and models for CO and HC emissions with respect to both vehicle age and mileage as variables are fairly described by a quadratic (or 2nd degree polynomial) curve. The emission equations derived for all three dataset conditions, i.e., entire, top 3 makes and top 16 models of petrol cars given in Tables 4.3, 4.4 and 4.5 – 4.8 and Tables 4.12, 4.13 and 4.14 – 4.17 respectively, can be used for predicting the CO and HC emissions with respect to the vehicle age and mileage.

2. It is further revealed that the emission characteristics of diesel-driven passenger cars of various makes and models for HSU emission concerning both vehicle age and mileage parameters are also reasonably depicted by a quadratic (or 2nd degree polynomial) curve. The emission equations computed for all three dataset conditions, i.e., entire, top 5 makes and top 13 models of diesel cars given in Tables 4.22, 4.23 and 4.24 respectively, can be used for predicting the HSU emission with respect to the vehicle age and mileage.

3. The scenario of the relative standing of different makes of petrol-driven passenger cars in terms of vehicle ageing effect on CO and HC emission is presented in Tables 4.10 and 4.11. It is found that HCIL and HMIL respectively, are the most affected makes in terms of CO and HC emission during idling condition while MSIL make is the most affected one during fast idling mode for CO and HC

emission both. Further, HCIL was found to be the least affected make in terms of CO emission in fast idling and HC emission in both idling and fast idling conditions, while MSIL make was seen as the least affected one only for CO emission during idle test mode. Model-wise relative standing finds that i10 and Wagon-R are the most affected petrol car models in case of CO emission during idling mode respectively while Celerio seemed to have been least affected in case of CO emission under either test condition as far as vehicle age is concerned. Going through the ageing effect on HC emission for petrol cars, the Nexon model was found to be the most affected one under both idling and fast idling condition while the Amaze model, the lease affected one.

4. The relative standing of various makes and models of petrol cars in terms of the effect of mileage on CO and HC emission is presented in Tables 4.19 and 4.20. It is revealed that MSIL make is the most affected one in case of CO emission during idling and fast idling both while HMIL is seen to be the most affected make in case of HC emission under both test conditions, as far as mileage effect is concerned. HCIL was found to be the least affected make for both CO and HC emissions under either case of testing modes. Model-wise analysis revealed a similar scenario as found in the case of ageing effect on CO and HC emissions with i10 and Wagon-R being reported as the most affected models in case of CO emission in idle and fast idle test modes respectively, whereas Nexon found its spot as the most affected model in case of HC emission in both test conditions. On the other hand, Amaze and Grand i10 models were found to be the least affected ones in the case of both CO and HC emissions under either test methods, respectively.

5. The status of makes and models of the diesel-driven passenger cars in terms of their relative standing for smoke emission (SE in HSU terms) in the account of vehicle age and mileage is shown in Tables 4.25 and 4.26 respectively. It reveals that MML and TKMPL makes are found to be the most affected ones in terms of SE due to age and mileage respectively while HMIL was found to be the least affected make in either case. In model-terms, XUV 500 and Verna were seen as the most affected models for their SE in respect of both age and mileage, whereas

Ciaz was reported as the least affected model in both aspects of tested diesel vehicles.

6. The study reported that the two tailpipe parameters, i.e., λ (measured) and AFR (calculated from the emission data), which were measured only for petrol-driven passenger cars showed a good correlation with both vehicle age and mileage being best represented by a quadratic (or 2nd degree polynomial) curve. This good degree of correlation was found in the case of all dataset scenarios, e.g., whole dataset, top 3 makes and top 16 models of petrol cars. As these two parameters are more of theoretical nature and not considered as tailpipe 'emission' parameters, their assessment is limited to graphical / tabular presentation.

7. The study found that the other two tailpipe emission parameters, namely, CO_2 and O_2 were not related to vehicular variables like age and mileage in any dataset scenario for petrol-driven passenger cars.

8. The study attempted to understand the effect of vehicle-related string variables, such as, vehicle body type, status of vehicle registration life half-past, vehicle kerb weight, transmission type, drivetrain type, emission norm @ manufacturing and maintenance category on tailpipe parameters in the case of both petrol and diesel-driven passenger cars. The variables, such as vehicle body type, status of vehicle registration life half-past, vehicle kerb weight, transmission type and drivetrain type were not found to be correlated to tailpipe emission and / or other parameters collected during the study. However, these parameters were analyzed to see the range of emission that was occurring in case of each string variable.

9. Another vehicle-related aspect, i.e., emission norm @ manufacturing was found to be directly linked to tailpipe emissions. It was revealed that the introduction of more stringent norm greatly improved the CO and HC emission in the case of petrol cars and SE in the case of diesel cars. In other words, BS IV-compliant cars had the lowest range of CO, HC and SE in any test scenario compared to the outgoing norms. It is seen that the MSIL and HMIL makes have the sharpest reduction in the emission levels while HCIL seemed to follow a rather lesser variation. Alto, Swift, i10 and Wagon-R recorded the highest reduction in CO

and HC (fast idling) between BS III and BS IV norms, while Santro and City reported a sharp reduction in HC (idling) values. In the case of diesel cars, BS IV-compliant MML and MSIL makes reported the sharpest decline in SE (HSU values) compared to BS III makes, closely followed by TKMPL, FIPL and HMIL. All diesel car models were BS IV-compliant (except Swift and XUV 500), although with a significant number of non-compliant cars mostly from XUV 500, Brezza, i20, Scorpio in descending order having Ecosport, Brezza, Fortuner and Ciaz as the lowest emitting cars.

10. The maintenance category of vehicles was found to be the most crucial aspect affecting the emission in both idle and fast idling test modes in the case of petrol cars and SE in FAST mode for diesel cars. The better-maintained petrol and diesel cars always had the lowest emission ranges and apart from a few exceptional cases (represented by the outliers in the scatter or boxplots), were always compliant with the in-use emission norms. In make terms, HCIL depicted the lowest range of CO and HC emissions and the quickest reduction in concentration ranges in both testing conditions with respect to better vehicle maintenance records, followed by MSIL; however, the maximum inconsistency was observed in the case of HMIL, specially in HC @ Fast idling scenario. Model-wise analysis showed similar trends as the entire dataset. Further, in the case of diesel cars, MSIL and MML had the maximum SE range for their 'unsatisfactory' category cars and the minimum emission range for their 'very good' maintenance category cars. All other makes fared in between. Similarly, models belonging to 'very good' category had the minimum HSU emission and vice-versa. Swift, Dzire, XUV 500 and Brezza were the worst performing cars belonging to the 'unsatisfactory' category of maintenance and exhibited the lowest emission ranges when the category changed to 'very good'

11. It is further revealed that engine variables, namely, engine capacity, maximum power, maximum torque, cylinder bore and piston stroke, number of cylinders, number of valves per cylinder and valve configuration do not seem to be related to tailpipe exhaust (CO, HC, CO_2 and O_2) or other parameters, such as λ and AFR in case of petrol cars and to SE (HSU) in case of diesel cars. The variables were

analyzed using scatter plots and checked for R^2 values yielded by quadratic trendlines in order to explore correlation, if any. Boxplots were drawn for string variables at a nominal scale for cases like the number of cylinders, number of valves per cylinder, engine aspiration, valve configuration and fuel mixing conditions and assessed for any specific pattern of change in measured values of dependent variables' ranges with respect to said engine variables.

12. Compliance status of all the vehicles tested during the emission measurement program towards in-use emission norms was also evaluated. All dataset scenarios of petrol cars depicted very high levels of compliance towards BS IV norm (the latest and the most stringent at the time of the present tailpipe emission testing program) and even better towards BS II for CO and HC emissions, the reason being the wider range of BS II (older) norm letting a higher number of cars pass through. HCIL exhibited the highest emission compliance levels or all emission test parameters followed by HMIL and MSIL makes. The maximum degree of non-compliance to both emission norms for all the testing parameters was depicted by MSIL make. Model-wise compliance status finds Amaze, Baleno, Eeco, Grand i10 and Nexon to be the most compliant models for various test parameters achieving almost 100% compliance towards BS IV norms. Diesel cars also reveal a very high level of compliance to both BS IV and BS III norms for HSU in FAST testing mode. Make-wise, HMIL performs the best towards both the emission standards, followed by MSIL and TKMPL. MML and FIPL have a higher percentage of non-compliance, especially for BS IV. Amaze, Verna, Duster, Brezza and Ciaz depict the highest degree of compliance for both BS IV and BS II emission norms of HSU under FAST showing almost 100% compliance. Figo leads the list of lowest levels of compliance followed by Scorpio, i20 and Swift models.

13. The tailpipe emission data collected during the emission testing program were also analyzed to assess the comparison of CO and HC emissions with respect to vehicle and mileage under both idle and fast idle testing conditions. It is concluded that if the fast idle test condition is also permitted in the country and is linked with the PUC certification process, the standardization procedure must look into the lowering of the values suitably than those prescribed for idle test

conditions. For e.g., for the upcoming BS standard, the CO @ Idling value of the norm may be brought down from 0.3 % to 0.1 % and at the same time, the CO @ Fast idling value may further be tightened from the existing 0.2 % to 0.05 %. On similar lines, the standard values of HC may be suitably made more stringent (say 50 ppm from the existing 200 ppm at idling condition) with the introduction of HC @ Fast idling into the PUC certification process, which may be fixed at 25 ppm or so.

14. The present study presented a unique approach to formulation of the Vehicular Exhaust Emission index or EEI. EEI was conceptualized so that depending upon numerical values constructed analyzing tailpipe emission data of cars, a scale can be presented stating the emission quality class or category of a vehicle. After careful consideration of the entire scenario of the resultant EEI values and categories, it is recommended to use the Maximum operator form (MOF) method for aggregation of indexing (EEI formation) based on the fact that it is free from eclipses and overlapping while presenting reliable outcomes on vehicles' compliance levels in narrower ranges of emission values.

The outcome of the study focusing on the effect of various vehicle and engine-related parameters on tailpipe emissions, status of compliance to emission norms and formulation of EEI for petrol-driven passenger cars of various makes and models in the NCT, Delhi has led to useful inferences. These can be used not only for inferring the emission of vehicles with respect to vehicle age and mileage, but also for the automobile manufacturing and maintenance sector, helping them manufacture more environmentally benign passenger cars. These 'better' vehicles would have long-lasting compliance with pollution control systems. On the other hand, EEI can keep the public informed about how good or bad their cars are, in terms of tailpipe emission and when to approach the vehicle service centre, ensuring that the cars remain compliant to the in-use emission norms. The high emitters may be identified easily based on their EEI class and attended to, for improvement following a quick-fix or a lengthy overhaul bringing them back to compliance level. Vehicles needing to be phased-out based on unsatisfactory EEI may also be marked easily and separated from the rest of the fleet.
This would go a long way towards reducing the vehicular pollution from passenger cars in the country and in the other developing nations reeling from urban air pollution and

looking forward to strengthening the existing I/M framework in a cost-effective manner.

Scope for future work:

- There is a scope to further refine the predictive emission equations with a model-wise more extensive data set. Few models had very less counting.
- The data collection may be widened to capture CO, HC and NOx also from the tailpipe emission to see how these parameters behave in case of both petrol and diesel-driven cars. Loaded tests may be taken up representing real-world driving and to check NOx trends.
- Idling testing scenario for CO_2, O_2, λ and AFR can be taken up and be checked for fast idling variations, if any.
- As the more stringent emission norms are being adopted worldwide, there may be scope for analyzing a similar or larger dataset or make or model or fuel-specific emission dataset in light of newer norms to ascertain any further reduction in vehicular emission characteristics in the future.
- The idle testing can be analyzed for petrol and diesel cars for impending BS VI norms whenever concentration cut-offs for compliance are introduced.

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